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ADDITIONAL DATA ON THE DELESSE-ROSIWAL METHOD

A. WILLIAMS POSTEL and H. M. LUFKIN,
University of Pennsylvania, Philadelphia, Pa.

ABSTRACT

Delesse-Rosiwal modal determinations of mineral composition from rock thin sections should not be computed to an accuracy within 1 per cent, unless the rock formation subjected to investigation is known to have uniform composition, or unless modal composition is to be related to chemical composition in a given sample.

When rock formations are known to have regional variability in mineral composition, modal determinations should be made to an accuracy just within the largest known regional variation for a single mineral constituent.

Statistical analysis shows that modal analyses accurate to within 10 per cent can be obtained by taking six traverses, 15 mm. in length, across the thin section, providing that the thin section is an adequate sample of the specimen from which it was made.

INTRODUCTION

A recent paper by Esper S. Larsen and Franklin S. Miller (1) gives an excellent description of the factors that must be observed to obtain Delesse-Rosiwal modal analyses of rocks of a given degree of accuracy.* The paper also discusses the different sources of error that may make it impossible to obtain a given degree of accuracy. Larsen and Miller draw particular attention to the error due to "failure of the thin section to provide a proper sample of the rock from which it is cut" (1, p. 262), a point not clearly emphasized by earlier authors. Larsen and Miller do not, however, discuss the significance of this important fact in relation to the desirability, or lack of it, of making very accurate modal determinations.

Using a modified type of the Wentworth stage, Larsen and Miller say that a modal analysis can be made accurate to 1 per cent, on rocks with an average grain size of 1 mm., by running 10 to 20 traverses, spaced about 1 mm. apart, over the thin section. Due to the tediousness of this procedure, it was decided to investigate the relationship of the error factor produced by normal variability of mineral composition for

* No bibliography is given on the Delesse-Rosiwal method, as a very complete one may be had in the paper cited.

a single rock formation to the degree of accuracy obtained from a given number of traverses per thin section.

SIGNIFICANCE OF THE SAMPLING POWER OF A THIN SECTION IN TERMS OF REGIONAL VARIABILITY

Obviously, when the accuracy of a modal analysis is referred to, it applies only to the thin section from which it was obtained; it does not indicate the possibility of great variation of mineral composition throughout a formation. In terms of time and expenditure of effort, it would appear inadvisable to make an analysis of an accuracy substantially greater than the normal regional variation, once the regional variability has been established. For example, if it has been established that a constituent of a rock varies 10 per cent in different parts of a formation, it is of no value, in general, to determine that constituent to 1 per cent in a given thin section, as that thin section is not a representative sample of the whole formation. Statistically, an accuracy of 1 per cent is not warranted unless the thin sections dealt with represent the same "population." Thin sections that show a variation of 10 per cent for a given constituent through a formation may represent samples gathered from different "populations." This line of reasoning was suggested by the statement made by Larsen and Miller in section 3 of their conclusion: "Failure of a thin section to sample a hand specimen or rock outcrop introduces a much larger error than that of the Rosiwall measurement on a thin section" (1, p. 271).

EXPERIMENTAL DATA

To investigate the relationship of the foregoing factors, a rock known to show regional variation in mineral composition was chosen: the Springfield aplitic granodiorite. This rock occurs as an intrusive in the Philadelphia area (2). Megascopically, it is a light gray rock, and appears to have uniform texture and composition. The grain size ranges from 0.5 to 2.0 mm., the average grain size being very close to 1.0 mm. The rock has a faint foliation due to the orientation of the biotite.

The Springfield aplitic granodiorite was also chosen because it illustrates another source of error mentioned by Larsen and Miller (1, p. 263), namely: the personal error caused by the inability of the investigator to be certain always of the identity of the mineral grains encountered during a traverse. A portion of the oligoclase present in the rock is untwinned, shows no cleavage, and has indices nearly identical

with quartz. On the raised platform of the micrometer stage it must be differentiated from quartz by the character of its extinction, and its inclusions, or by etching with hydrofluoric acid. If etching is not resorted to, the error of confusion between these two components cannot be eliminated, as sections nearly perpendicular to an optic axis give similar hazy extinction, and the inclusions are not always reliable.

All the modal analyses reported here were made with the modified Wentworth type of stage. The procedure followed is that described by Larsen and Miller.

Table 1 demonstrates the regional variation in mineral composition in the Springfield aplitic granodiorite. This table also gives the standard deviation of the mean for the major constituents. To compute the standard deviation, the percentage composition of the major constituents was carried out to two decimal places. The standard error of the mean* shows the value of the mean which one would expect in 95 per cent of the cases, if one adds or subtracts twice the standard error of the mean from the mean of the sample. In all cases this is very small in comparison to the mean itself.

Consideration of Table 1 shows that the largest variation for any single constituent, quartz, is 12.3 per cent; the microcline content shows a variation of over 9 per cent.

To establish a standard composition, a large typical hand specimen of the aplite was collected. From this specimen four parallel and closely spaced thin sections were made. The volume of rock needed to make these sections was approximately 1 cubic inch. This operation was carried out in order to get several thin sections of as nearly identical composition as possible, so as to permit the addition of traverse lengths obtained from the different slides. These thin sections are designated in the tables as S 16-1, S 16-2, S 16-3, and S 16-4. S 16-1 was unetched, but to eliminate the error of confusion between quartz and oligoclase, half the areas of S 16-3 and S 16-4, and the whole area of S 16-2, were etched with hydrofluoric acid before the cover glasses were applied.

A comparison of modal compositions, based on thirty-eight etched and thirty-eight unetched traverses, showed an error for the unetched determinations of +3.8 per cent for quartz, and -3.7 per cent for oligoclase, the oligoclase being erroneously included with the quartz. (Student errors often went well over 10 per cent.)

* Standard deviation of the mean=

Standard deviation of the sample

Square root of the number of individuals in the sample

TABLE 1

Specimen	S 16 ^a	S 16-1 ^a	R 1 ^b
Number of traverses	20	20	20
Total length in mm.	371.16	362.52	373.60
Area of section ^c in sq. mm.	425	510	425
	SDM ^d	SDM	SDM
Biotite	8.2 ±0.55	7.6 ±0.42	9.1 ±0.55
Microcline	23.9 ±1.62	16.8 ±1.11	14.7 ±1.72
Oligoclase	45.4 ±1.19	41.1 ±1.13	46.5 ±1.99
Quartz	20.7 ±1.52	33.0 ±1.27	26.9 ±1.29
Accessories	1.8	1.6	2.9

^a These specimens were taken from the same dike, about two feet apart.

^b This specimen came from a dike about 9½ miles to the northeast of locality S 16 and S 16-1.

^c The areas of the sections were obtained by multiplying the average length of the section by the length of the average traverse.

^d The standard deviation of the mean.

Table 2 gives the modal compositions as computed from the etched sections. As the change in composition from an analysis based on thirty-eight traverses to an analysis based on fifty-three traverses was less than 1 per cent for any constituent, the latter analysis was taken as the standard for comparison; hereafter it will be referred to as the standard.

In order to see what variation in modal composition would occur, in terms of the standard, when composition was determined on the basis of a small number of traverses, several modal compositions were calculated on the basis of three and five traverses. Table 2 *a* gives the composition of S 16-2 as computed from partial traverses. The partial traverses were taken by spaced selection from the traverses used to establish Table 2; the individual numbers of the traverses used are designated in the table. To the right of each composition column is the percentage variation of the partial composition from the standard, Column 1, Table 2.

This table shows that the variations from the standard in the compositions calculated from the short traverses are less than the maximum regional variation for quartz and microcline, as shown in Table 1. Compositions based on the selection of other combinations of traverses, i.e., the fifth, fifteenth, and twentieth traverses, and the second, sixth, eleventh, sixteenth, and nineteenth traverses give variations from the standard that are smaller than those shown in Table 2 *a*.

TABLE 2

Specimen	S 16-2 S 16-3 S 16-4	S 16-2 S 16-3 S 16-4	S 16-2	S 16-3	S 16-4
Number of traverses	53	38	28	10	15
Total length in mm.	932.87	705.06	466.92	185.90	280.05
Area of section ^a in sq. mm.			510	290	340
Biotite	8.7	8.5	8.8	8.1	8.7
Microcline	17.2 ^b	17.2 ^b	17.2 ^b	17.6 ^c	18.4 ^c
Oligoclase	43.0	42.8	43.4	40.6	42.2
Quartz	29.8	30.2	29.2	32.4	29.1
Accessories	1.3	1.2	1.3	1.2	1.5

^a This refers only to the etched area of the thin section.

^b Microcline content computed from the average obtained from the unetched portions of S 16-3 and S 16-4, and S 16-1.

^c Microcline content calculated from the unetched portions of the sections.

TABLE 2 a

Specimen	S 16-2		S 16-2		S 16-2	
Numbers of the individual traverses taken	1st, 10th, 20th		1st, 14th, 28th		1st, 5th, 10th, 15th, 20th	
Total length in mm.	48.94		49.48		85.13	
	%VS ^a		%VS		%VS	
Biotite	8.7	0.0	12.1	+3.4	9.3	+0.6
Microcline	17.2	0.0	17.2	0.0	17.2	0.0
Oligoclase	36.6	-6.4	38.8	-4.2	37.1	-5.9
Quartz	36.0	+6.2	30.0	+0.2	34.4	+4.6
Accessories	1.4	+0.1	1.8	+0.5	2.0	+0.7

^a Percentage of variation from the standard.

+ Above the standard.

- Below the standard.

Table 3 gives the modal compositions determined from the unetched areas of S 16-1, S 16-3, and S 16-4, and their percentage variations from the standard, Column 1, Table 2. Table 3 also shows that fewer traverses give only small variations from the standard, and if the oligoclase-quartz correction factor is applied, the variation becomes negligible. Comparison of the modal compositions as obtained from the two halves

of S 16-1 (ten traverses for each half) shows that there is less than 1 per cent variation between the halves for all constituents.

TABLE 3

Specimen	S 16-1		S 16-3			S 16-4			S 16-1 S 16-3 S 16-4	
Number of traverses	20		10			8			38	
Total length in mm.	362.16		184.76			146.76			702.45	
	%VS		%VS SDM ^a			%VS SDM			%VS	
Biotite	7.6	-1.1	7.2	-1.5	±0.72	7.9	-0.8	±1.11	8.1	-0.6
Microcline	16.8	-0.4	17.6	+0.4	±1.26	18.4	+1.2	±1.33	17.2	0.0
Oligoclase	41.1	-1.9	38.6	-4.4	±2.57	38.2	-4.8	±1.21	39.1	-3.9
Quartz	33.0	+3.2	35.0	+5.2	±1.66	34.1	+4.3	±1.73	34.0	+4.2
Accessories	1.6	+0.3	1.6	+0.3		1.4	+0.1		1.5	+0.2

^a Standard deviation of the mean.

Table 3 *a* gives modal compositions obtained from unetched S 16-1 on the basis of partial traverses, and the percentage variations from the standard, Column 1, Table 2.

TABLE 3a

Specimen	S 16-1		S 16-1	
Numbers of the individual traverses taken	1st, 10th, 20th		1st, 5th, 10th, 15th, 20th	
Total length in mm.	52.54		89.42	
	%VS		%VS	
Biotite	7.7	-1.0	7.0	-1.7
Microcline	14.1	-3.1	15.3	-1.9
Oligoclase	39.6	-3.4	42.0	-1.0
Quartz	37.3	+7.5	34.2	+4.4
Accessories	1.3	0.0	1.4	+0.1

In comparing the modal compositions given in Table 3a with the standard, it can be seen that the variations are small—smaller than the regional variation shown in Table 1. It is also to be seen that the variations of the partial modal compositions obtained from the unetched

sections are smaller than the variations obtained from the etched sections; this may be due to variability in the quartz-oligoclase confusion factor.

Partial analyses were also computed for the unetched thin sections S 16, and R 1, based on the first, tenth, and twentieth traverses. These partial analyses did not vary from the compositions as determined by the full twenty traverses by more than 5 per cent for any constituent.

STATISTICAL TREATMENT

It was considered advisable to check the foregoing data by statistical methods, in terms of the principles involved in sampling. This was done in an attempt to show that the individual sections were homogeneous within themselves, but that when they were compared with each other they could not be considered, as a group, a homogeneous sample of the Springfield aplitic granodiorite. To do this the readings for each traverse were weighted inversely for each mineral with the length of each traverse, and multiplied by 100, so that each mineral is given in terms of its percentage. It seemed best to make use of the standard deviation rather than the mean deviation, since the standard deviation can be better used to determine the variations between the means of the different thin sections, and also those in which the traverses were divided into two sections of 10 traverses each.

The method employed here was that of making use of the value "*t*" to determine whether the difference of the means of the different parts of the thin sections, and between the thin sections, was significantly different, or whether they came from the same, or different, theoretical "populations." The value "*t*" gives a precise measure of the variation of the differences between the means of the random samples drawn from a homogeneous "population." The size of the samples has no effect on the values of "*t*." The tables for the values of "*t*" for different percentages may be found in the references cited.

The value of "*t*" used was that in which the values of the difference were less than the 5 per cent level, or that the probability was 95/100 that they came from the same "population" (3). It may be said that a value of "*t*" less than the 5 per cent level means, generally, that the samples came from the same theoretical "population," or from similar random samples. The method is that of Snedecor (4, pp. 71-76, 182-203).

In the thin sections S 16, S 16-1, and R 1, the traverses were separated into two groups of ten consecutive traverses. In all these slides the values of "*t*" were less than the 5 per cent level, so that each part of the slide can be considered as belonging to the same set of data.

Using the same method, the thin sections were compared in the following manner: S 16-1 with S 16, S 16-1 with R 1, and S 16 with R 1. Table 4 shows the results.

TABLE 4

	S 16-1, S 16	S 16-1, R 1	S 16, R 1
Biotite	Same	Different	Same
Microcline	Different	Same	Different
Oligoclase	Different	Different	Same
Quartz	Different	Different	Same

Table 4 shows that, in general, the major constituents of these three thin sections are not from the same "population," and therefore they do not represent an adequate sample of the rock formation.

It was also decided to test, statistically, the assumption that the slides S 16-1, S 16-3, and S 16-4 represented a homogeneous sample of the specimen from which they were taken. No significant differences between the means of the different minerals were found. In this case the difference between the three means for the different minerals was again less than the 5 per cent level, which indicates that they come from the same "population," or from the same random sample.

The question in regard to the number of traverses necessary to obtain a mean comparable, i.e. within the 90 per cent level, was investigated. It was found that this degree of accuracy could be obtained by basing modal composition on 6 traverses, 15 mm. in length. As a check, samples of 6 traverses were selected by the use of random sampling numbers (3). Random sampling numbers permit the reduction of a large bulk of data to a smaller group that may be more readily handled, and give an indiscriminant sampling of the whole. Taking S 16-1, it was found that all the means were comparable (5, p. 118).

DISCUSSION AND CONCLUSION

Consideration of the foregoing data would seem to make it a practical procedure to gauge the number of traverses necessary for a series of Delesse-Rosiwal analyses in terms of the regional variation of the rock type being considered. The accuracy of each analysis, as controlled by a given number of traverses, should be kept just below the largest known regional variation.

The modal composition tables indicate that an analysis accurate to about 6 per cent can be obtained by taking 5 well spaced traverses across

the thin section, if the average grain size is about 1 mm. The use of random sampling numbers puts this more concisely, and shows that an analysis can be made accurate to within 10 per cent if 6 traverses, 15 mm. in length, are determined.* In comparison to the work involved in determining analyses to an accuracy within 1 per cent, the time and effort saved is considerable, if this procedure is adopted, particularly, when no significance can be attached to an analysis that is accurate to within 1 per cent if it fails to sample the formation.

Two plans of approach to a regional problem involving large numbers of thin sections may be suggested. Three or four thin sections may be analyzed to an accuracy within 1 per cent, according to the criteria set up by Larsen and Miller (1, pp. 271-272), to establish the regional variability; all succeeding thin sections can then be investigated on the basis of fewer traverses, to an accuracy within the regional variation. The alternative procedure is that a series of thin sections may be analyzed to an accuracy within 10 per cent; then all variations above 10 per cent may be assumed to be due to the regional variation factor.

It should be emphasized that some circumstances necessitate Delesse-Rosiwal analyses of much greater accuracy than advocated here. This is certainly true when rock formations of uniform composition are being subjected to investigation, or when chemical composition is to be related to modal composition.

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* The average length of traverse used to compute the modal composition tables was 17 mm.

THERMAL STUDIES OF ORTHOCLASE AND MICROCLINE

JOSEPH L. ROSENHOLTZ AND DUDLEY T. SMITH,
Rensselaer Polytechnic Institute, Troy, New York.

ABSTRACT

Thermal studies were conducted on crystallographically oriented sections of orthoclase and microcline from 0° to 1000° C. Coefficients of linear expansion are given for microcline parallel to each axis. Mean values parallel to a increase from 14.97×10^{-6} to 17.85×10^{-6} . The maximum mean coefficient parallel to b is 1.18×10^{-6} and is 1.30×10^{-6} parallel to c . A series of eleven abrupt volume changes are listed for orthoclase and twenty for microcline. A comparison of adularia, orthoclase and microcline is presented.

INTRODUCTORY

The thermal study of orthoclase and microcline is of considerable interest because of the similarity in many of their properties and the controversial nature of their relationship. The status of the orthoclase-microcline problem has been presented succinctly by Alling (1). Much valuable data is available as a result of a number of investigations on changes in optic angle, refractive indices and density. The results of this investigation may be of further aid in the clarification of the relationship of the potash feldspars.

The microcline selected was a large, flesh-colored crystal from Bedford, New York. Its density is $d_{20} = 2.544$ and the refractive indices are: $\alpha = 1.518$, $\beta = 1.522$, $\gamma = 1.525$. The chemical analysis is given in Table 1. This corresponds to the composition $\text{Or}_{83.5}\text{Ab}_{16.5}$. Three sections, approximately $4 \times 4 \times 10$ mm. were cut parallel to each crystallographic axis and these sections were studied from 0° to 1000° C. by the methods previously

TABLE 1.* ANALYSIS OF MICROCLINE FROM BEDFORD, NEW YORK

SiO ₂	65.10
Al ₂ O ₃	18.80
Fe ₂ O ₃	0.10
FeO	
MgO	0.09
CaO	0.02
Na ₂ O	1.99
K ₂ O	14.14
TiO ₂	0.01
H ₂ O+	0.11
H ₂ O-	0.01
	100.37

* Analysis by Laboratory for Rock Analysis, University of Minnesota.

described by the authors (2). Observations were made at intervals of 10° for all sections and at intermediate points where abrupt volume changes occurred.

Similar studies were made on oriented sections of orthoclase cut from flesh-colored crystals from Good Springs, Nevada. This material, in the aggregate, has the composition $\text{Or}_{71.8}\text{Ab}_{23.8}\text{An}_{2.4}$. Since the crystals were slightly altered, only the volume changes will be reported in detail at this time.

EXPERIMENTAL RESULTS

The mean coefficients of linear expansion for microcline are given in Table 2. In general, the values parallel to a closely approximate similar values for adularia (3). The coefficients parallel to b and c are somewhat more divergent. A comparison of corresponding sets of data reveals one very striking difference, namely, that all values for microcline increase for each orientation from 800° to 1000° , while all values for adularia decrease from 900° to 1000° . The expansion values obtained for the

TABLE 2. MEAN COEFFICIENTS OF LINEAR THERMAL EXPANSION FOR MICROCLINE

0°C. to	Parallel to a $10^6\delta_m$	Parallel to b $10^6\delta_m$	Parallel to c $10^6\delta_m$
100°	14.97	0.49	0.49
200°	16.19	0.23	0.45
300°	16.34	0.02	0.50
400°	16.46	0.03	0.65
500°	16.77	-0.04	0.85
600°	16.82	0.02	1.00
700°	17.05	0.09	1.06
800°	17.09	0.18	1.22
900°	17.29	0.56	1.29
1000°	17.85	1.18	1.30

Good Springs orthoclase all decreased from 900° to 1000° as did those for adularia. It is concluded, therefore, that there is a distinct difference in behavior during expansion between these monoclinic and triclinic potash feldspars. The curves shown in Fig. 1 display this difference.

Numerous sudden volume changes, made evident by abrupt changes in the rate of expansion, were observed for both orthoclase and microcline. These are given in Table 3, and the previously reported (3) values for adularia are included for comparison, all temperatures being $\pm 5^\circ \text{C}$. Kôzu and Saiki (4) reported fewer volume changes than were observed in these investigations. A full comparison, including their results, may be obtained from Fig. 2.

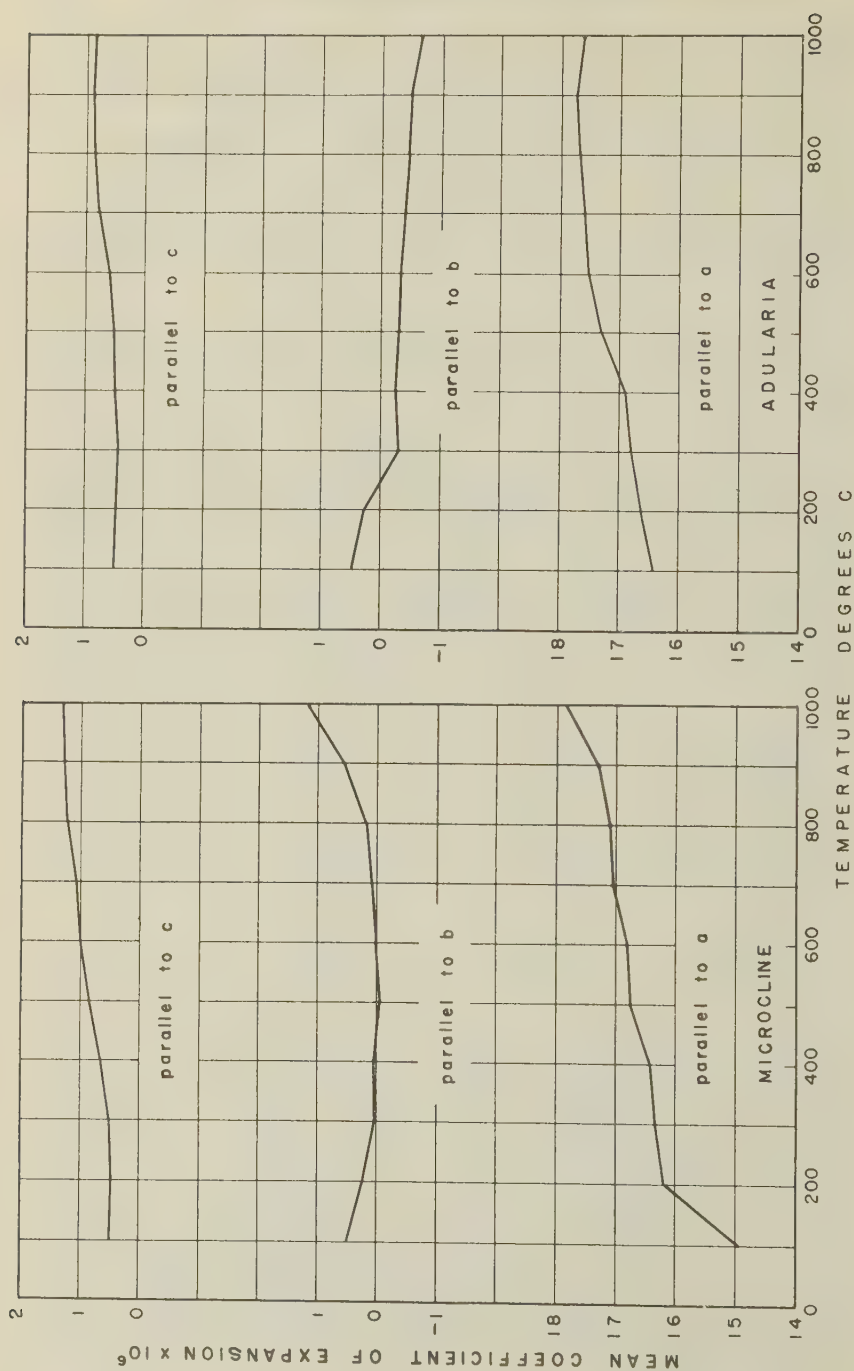


FIG. 1. Mean coefficients of linear expansion (from 0°) for microcline and adularia.

TABLE 3. TEMPERATURES OF ABRUPT VOLUME CHANGES IN MICROCLINE, ORTHOCLASE AND ADULARIA

Microcline	Orthoclase	Adularia
100°C.		
120°		120°C.
150°		
190°	190°C.	
	245°	
265°		260°
		285°
300°		
400°	400°	400°
445°		
480°		475°
505°	500°	
570°	560°	560°
600°		
	615°	
645°	670°	680°
770°		
725°		740°
770°		
	800°	
825°		820°
		855°
	870°	
895°	895°	900°
950°		950°
	970°	
985°		

DISCUSSION

Kôzu and Saiki (4) studied flesh-colored orthoclase from Arendal, yellow orthoclase from Madagascar and amazonstone from Pikes Peak. An examination of the mean coefficients which they obtained for these feldspars shows that an increase occurred for all samples in all directions from 900° to 1000°, with the exception of a single sample of Arendal orthoclase parallel to *b*, which decreased in this temperature range. A comparison of the amazonstone with the microcline described above cannot be accurate because of possible differences in chemical composition. Their mean values (from 20°) for the amazonstone at 1000° are: $10^6\delta_{m\parallel a}=21.05$, $10^6\delta_{m\parallel b}=4.80$ and $10^6\delta_{m\perp base}=14.30$. Their *a* values, though high, are in the approximate range reported here for microcline; their *b*

values appear extremely high; the divergences in the values of the several feldspars which they examined in the direction perpendicular to the base seem contradictory among themselves.

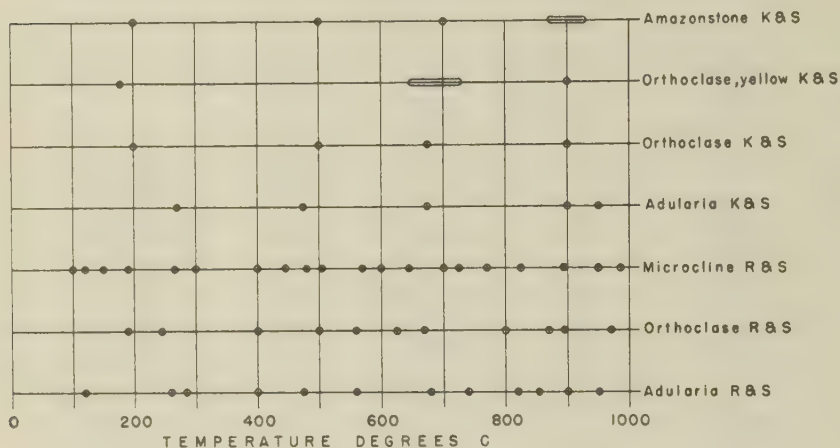


FIG. 2. Volume changes in adularia, orthoclase and microcline

There are some abrupt volume changes which are common to two of the three feldspars and other changes which appear to be characteristic of each separate feldspar. It is peculiar that there is a much greater similarity in points between microcline and adularia than between orthoclase and adularia. Spencer (5) found similar behavior in his heating studies as they related to changes in optical properties. It is apparent from Fig. 2 that the volume changes at 400° and 895° , and possibly at 560° , are common to the three feldspars studied, regardless of their composition or manner of origin. It is to be observed, particularly, that the change at $895^{\circ} (\pm 5^{\circ})$ is common to all samples examined by both groups of investigators. It is suggested, therefore, that the above temperatures correspond to inversion points. Accordingly, if 895° is an inversion point, the assumed stability of microcline up to its melting point would no longer be valid. The authors, on the basis of this investigation, question such stability.

Kôzu and Saiki found no change at 950° , except for adularia. This point was observed not only for adularia but also for microcline; it did not occur for orthoclase.

It is clear that microcline displays almost twice as many volume changes as do either adularia or orthoclase, the numbers being 20, 12 and 11, respectively. This, together with the difference in behavior dur-

ing expansion at high temperatures discussed above, seems sufficiently definite, *per se*, to establish the separate identities of orthoclase and microcline.

ACKNOWLEDGMENT

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THE MINERALOGY AND PARAGENESIS OF THE VARISCITE NODULES FROM NEAR FAIRFIELD, UTAH. PART 2

ESPER S. LARSEN, 3D, *Harvard University, Cambridge, Mass.*

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DESCRIPTION OF STRUCTURES AND THEIR INTERPRETATION

The Fairfield variscite and associated phosphates occur almost entirely in nodules. A small amount of the material is in angular fragments, probably breccia fragments of former nodules. The nodules range in size from a quarter of an inch to two feet or more in diameter; the commonest range of sizes is from one to three inches. They are generally spherical in form, some are flattened. A few show an interference in shape where two nodules grew into contact.

RELATION OF NODULES TO ENCLOSING MATERIALS

Most of the nodules are enclosed in brown earthy limonite which contains abundant calcite disseminated through it. The calcite is probably residual from the original limestone. No limonite has been found inside any of the nodules, although in some the outer layer of pseudowavellite is slightly iron-stained. Moreover, the limonite tends to be concentrated around the phosphate nodules. If limonite had been present before the introduction of pseudowavellite, probably some of it would have seeped into the fractures in variscite later filled by pseudowavellite; such does

not occur. Thus the limonite replaced the limestone and filled fractures in chert fragments after the phosphate minerals were deposited.

Many of the nodules have masses of chert attached to their surfaces. The chert is in angular fragments up to an inch across, very loosely held together, and with wide unfilled openings between many of the fragments. The brecciation of the chert must have preceded the formation of the nodules since the nodules commonly show very little fracturing while the chert surrounding them is badly shattered. Small crystals of calcite and aggregates of tiny quartz crystals grow upon the walls of the chert fragments. Limonite and small pseudowavellite nodules are cut by thin seams of coarse calcite and of fine quartz.

A few small nodules have been found embedded in angular fragments of gray alunite occurring mixed with angular fragments of chert. Others have angular fragments of alunite attached to their walls. Thus the alunite must have preceded the formation of the phosphates and the strong brecciation of the chert.

Within some of the nodules are large, angular fragments of black chert surrounded by thin pseudowavellite bands; the fragments are very slightly rounded at their corners, suggesting slight replacement. The masses containing these chert fragments are themselves highly brecciated, and may represent a mechanical mixture of chert and phosphate fragments (variscite at the time of brecciation).

Very thin black seams of fine quartz cutting variscite, and preceding the deposition of pseudowavellite (see later), are rare. One polished specimen, Fig. 1, is made up of small rounded, partly altered variscite nodules between which is found this same black quartz; it is definitely earlier than the alteration products of the variscite, but seems in part to have filled in between an aggregate of small variscite nodules, perhaps by replacement of calcite (limestone).

GENERAL DISTRIBUTION OF THE MINERALS WITHIN THE NODULES

The general distribution of the minerals within the nodules has been described by Larsen and Shannon (1930*b*, pp. 308–309). Most of the nodules are formed of successive, locally separated shells of fibrous, fine-grained, yellow pseudowavellite, inside of which is an irregular coating of granular porous aggregates of yellowish pseudowavellite; the central portions are generally hollow. Some nodules still contain cores of brilliant green variscite; these have fine, banded shells of pseudowavellite, commonly separated, as the outer material, inside of which is a white dense layer completely surrounding the variscite kernel. It is in the open lenticular spaces between the kernels and the outer yellow shells that the rare crystal-forming species are generally found. Through the green

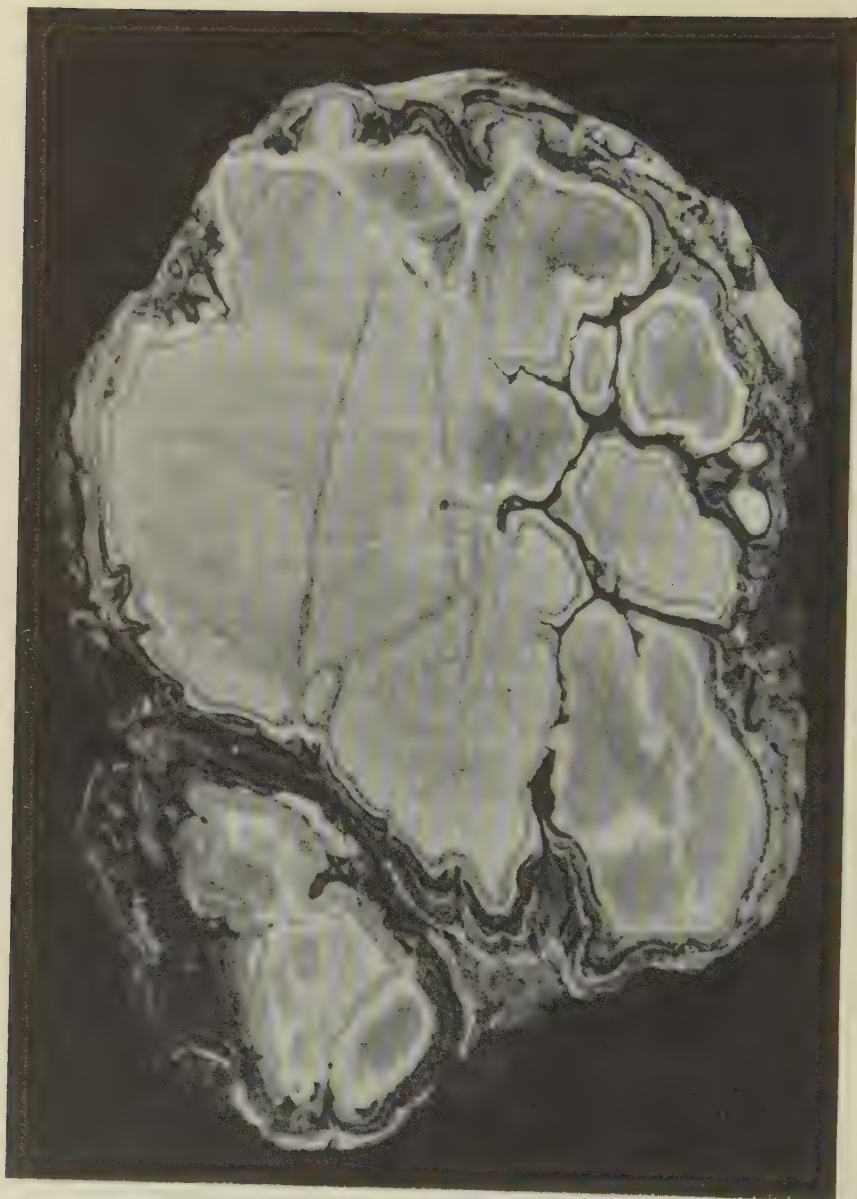


FIG. 1. Photograph of a polished variscite nodule. The black seams are fine-grained quartz; the gray seams in the center of the nodule are a darker green variscite in a normal variscite. The white shell surrounding the variscite is a dense pseudowavellite; the outer finely-banded material is the early pseudowavellite. $\times 1$

variscite kernels run occasional banded veinlets of pseudowavellite; many of the kernels contain isolated banded spherulites of pseudowavellite, or of wardite and millisite.

DETAILED DESCRIPTION OF THE STRUCTURES AND THEIR SIGNIFICANCE

Below are given descriptions of the manner in which each mineral occurs in the nodules, and interpretation of its significance. Part is a repetition of the descriptions given by Larsen and Shannon. The minerals are taken up roughly in their order of decreasing abundance, which also roughly follows their sequence.

Variscite

Variscite is the dominant mineral in many of the nodules and probably was the original mineral of all of them. It invariably occurs in the interior of the nodules as a massive, fine-grained, compact and rounded core; two or more residual kernels may occur in one nodule. Some variscite kernels are cut by fine seams, and surrounded by a thin band of darker green variscite (Fig. 1). This is probably due to a slight coarsening of grain around the periphery and along incipient cracks where accessibility to solutions was greater.

All the variscite seen in this study has a very fine and even grain size, about 0.01 mm. or less in diameter. Larsen and Shannon (1930*b*, p. 333) found coarser variscite as crystalline plates in the white powdery layer surrounding the green kernels; this was not seen by the writer.

There is no doubt but that the green variscite was the first mineral deposited. All the other minerals associated with it either replace it or occur in or on minerals which have replaced it. The coarser variscite found by Larsen and Shannon and mentioned above, probably recrystallized from residual variscite remaining after the replacement of variscite by white powdery pseudowavellite.

Some nodules have cores of variscite much smaller than the cavities they occupy, and not attached to the cavity walls at any point; these cores have very definitely been partially dissolved after the replacement by the outer pseudowavellite shells. This is evidenced both by their smallness in relation to the size of the cavities they occupy, and more definitely by the fact that small veinlets of pseudowavellite which formerly traversed the larger cores, now project outward from the surface of the variscite kernels into space as thin plates. Solutions with a selective solvent action, rather than a replacing action, must have dissolved the variscite, leaving the pseudowavellite unattacked. A precisely similar structure has been developed artificially by the use of a hot KOH solu-

tion on fragments of variscite containing pseudowavellite veinlets. This is discussed later.

It may be that the original variscite nodules were deposited as colloidal masses (gels), but only slight evidence supports this view. Some of the polished variscite displays discontinuous, anastomosing films of deeper green variscite, as noted above. Many of these healed cracks do not extend to the edges of the nodules, and may in part be due to internal tensional forces. Similar healed cracks in chert nodules are considered shrinkage cracks caused by a coarsening of a silica gel. Other evidences of colloidal origin are absent, unless fineness of grain and nodular form can be considered as such. Metacolloidal textures are in general absent from the variscite of other localities; some carry variscite crystals in vugs, as in the Arkansas deposit and the "lucinite" of Lucin, Utah. Banding is rarely seen, and is absent in the Fairfield variscite. It seems best to consider the variscite as deposited in the crystalline state in which it occurs at present.

Pseudowavellite

Pseudowavellite is the most abundant phosphate mineral in the deposit, and makes up the bulk of most nodules. It occurs as thin, banded and simple shells and veinlets, of which some contain intergrown deltaite: as spherulitic aggregates; as banded spherules; as irregular to angular masses in variscite; and as pseudomorphs after gordonite.

The great majority of the nodules contains nothing but pseudowavellite, as tight-fitting, thin, yellow shells surrounding a central hollow core. Lining the walls of the central cavity are granular aggregates or spherules of pseudowavellite which in some nodules very nearly filled the cavity.

The nodules still containing variscite are completely surrounded by a layer, up to a centimeter thick, of banded pseudowavellite; a few carry outer bands which are fairly coarse grained and rudely spherulitic and which contain abundant deltaite intergrown with the yellow pseudowavellite. Such deltaite has been seen in only a few specimens. Generally, the outer bands are composed of subparallel or matted fibers of pseudowavellite, but some are coarse grained and vitreous. The various layers composing the outer shell of pseudowavellite are continuous around all, or a large part, of the nodule. Commonly veinlets up to a few millimeters wide cross the nodules; these veinlets are banded and their banding is continuous with the banding of the outer shell. Thus, they must have formed simultaneously. Many of the pseudowavellite veinlets have a central black line made up of fine-grained quartz; some of the sharp indentations and cusps of the outer yellow shells have a similar central line of quartz. The banding of the pseudowavellite is symmetrical on

either side of these veinlets. The original variscite must have been fractured, and fine-grained quartz deposited in the tiny openings. These fine veinlets of quartz gave access to the replacing pseudowavellite solutions, and it was along and outward from these veinlets that the early pseudowavellite was deposited. Figure 1 shows these black quartz veinlets upon which, in part, the pseudowavellite has centered. In nodules in which the original fracturing made a breccia of the whole mass, the introduced quartz formed a "boxwork" upon which banded pseudowavellite deposited; in a few specimens the central part of each "box" is hollow, giving a honey-comb effect to the pseudowavellite. In a few of the "boxes" are small residual cores of variscite. These have formed in a manner identical to the boxwork of wardite and millisite, built up on fine pseudowavellite veinlets, and described below. It serves to indicate further the replacement character of the pseudowavellite.

Small banded spherules and lenses of yellow pseudowavellite occur in the variscite. Some of these are isolated, but others occur as bulges along fine pseudowavellite veinlets. The veinlets along which they developed are offshoots from the main outer pseudowavellite bands, and the sequence of the banding in them is similar to that in the outer bands; thus these are related to the early pseudowavellite.

Inside the outer shell of pseudowavellite is commonly a discontinuous band, or shell, of wardite and millisite, either in colloform bands or spherules; the spherules commonly grow into open cavities toward the center of the nodule. Beyond the wardite-millisite band, and commonly separated from it by a discontinuous irregular cavity, is another shell of dense yellow roughly banded pseudowavellite completely enclosing the variscite core. Veinlets from the outer pseudowavellite shells cut the inner dense pseudowavellite shell; but commonly the inner shell contributes locally toward the veinlet. Thus the veinlet is made up of initially banded pseudowavellite, the bands of which are continuous with the bands of the outer shell, and on either side of these are additional bands of more dense pseudowavellite continuous with the bands of the inner shell of the mineral. Thus the veinlet must have been there before the inner pseudowavellite bands were deposited.

In a few specimens the inner layer of pseudowavellite is made up of thin, slightly separated, successive shells, separated as though through shrinkage. However, each shell follows very faithfully the outline of the shell preceding and succeeding it. Moreover, the width of separation of two successive shells is very constant over considerable areas and even around sharp turns. The shells clearly have been formed by replacement of the variscite, so that the reasonable explanation of their separation is to assume a period of variscite solution between successive periods of

replacement to form the shells, rather than considering it a shrinkage (colloidal) phenomenon. There is ample evidence elsewhere to prove that variscite was removed by solution at one or more times during the mineralization. Very finely fibrous, white, powdery pseudowavellite forms a thin coating over these separated shells.

Many of the variscite kernels are completely surrounded by a tight-fitting, white, chalky layer of pseudowavellite (deltaite?), about a millimeter or more thick. This layer generally ends sharply against the variscite, but in places the contact with the variscite is gradational and irregular, indicating replacement of the variscite rather than a coating. In a few specimens a white, powdery layer of pseudowavellite coats variscite and separated shells of pseudowavellite, and occurs irregularly on many of the crystal-forming minerals occurring in the cavities. It is later in the sequence than most, if not all, of the minerals in the nodules. A similar late pseudowavellite occurs as tiny isolated oolites perched upon late cavity minerals.

Pseudomorphs of pseudowavellite after gordonite have been seen in two specimens. In one, a group of gordonite crystals has been completely replaced by a porous aggregate of pseudowavellite. Other gordonite crystals have been replaced by a very fine-grained, white pseudowavellite, leaving well-formed but fragile pseudomorphs.

Wardite-Millisite

Wardite and millisite nearly always occur together in the nodules; they comprise the gray banded layers and spherules, the blue to gray crystalline crusts, and white, coarse-grained masses near tan pseudowavellite. They occur as successive alternating layers of gray to white, dense millisite and pale blue to colorless vitreous layers and crusts of wardite. In general, the centers of the spherulites and the earlier bands of the banded forms are made up mostly of millisite, while the proportion of wardite increases considerably away from the centers and the earlier bands.

Many of the variscite kernels contain spherules of wardite and millisite up to a centimeter in diameter. Some are perfectly round, isolated forms in a broad field of variscite, but more commonly they occur sparsely distributed along cracks in the variscite, and many of these appear to have been offset by micro-faulting. Some may have been offset by such a movement, but most have formed as two separate half spherules from separate centers on either side of the fracture, and never represented a single complete spherule. This is shown by the fact that the bands in the spherules, when they approach the crack, turn slightly and tend to follow the crack, thus indicating that the crack influenced their original

form. Moreover, there seems to be no case in which there is any evidence of microscopic brecciation or lack of fit on opposite walls of the crack. A few of the offset spherulites are veined by vitreous yellow pseudowavellite, and are completely surrounded by a thin band of dense pseudowavellite; the vitreous material is earlier than the spherulites, and the dense material later, as is indicated by other structures in the same specimens. Figure 2 shows wardite-millisite spherulites veined and surrounded in this way. Some spherules center upon the walls of pseudowavellite veinlets and project outward as hemispherical forms into what was originally

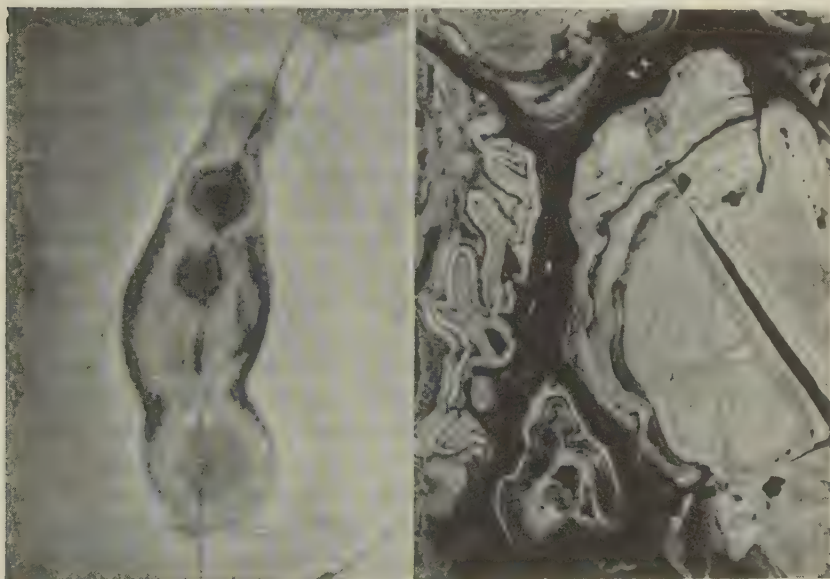


FIG. 2. Photograph showing small wardite-millisite spherules cut by a very thin veinlet of pseudowavellite and surrounded by pseudowavellite. The bands of the spherules tongue out when they meet the thin veinlet. $\times 2$.

FIG. 3. Photograph of delicate banding of wardite and millisite. The inward protrusions of the bands in places follow veinlets of pseudowavellite. Offsetting in the banding is not due to fracturing after formation of the bands. $\times 2$.

variscite. The pseudowavellite veinlets upon which the spherules are centered are in all cases continuous with the outer, early, banded shells of pseudowavellite, and the more dense pseudowavellite which surrounds the spherulites in all cases is continuous with the inner, more dense shell of pseudowavellite. Many of the spherules and hemispherules have coalesced where they grew together, and form scalloped, continuous bands around a number of centers.

Alternating layers of wardite and millisite form angular and waving bands immediately inside the outer pseudowavellite shell (Fig. 3). The angular banding in general conforms to the surface of the pseudowavellite on which it grew, while the wavy bands represent coalesced hemispherules whose closely spaced centers lie upon the pseudowavellite surface. Abrupt inward protrusions of the wardite-millisite banding is more or less symmetrical on either side of a central line, made up either of a thin veinlet of vitreous pseudowavellite or wardite, or in some, an indefinite preexisting crack. These pseudowavellite veinlets have banding continuous with the banding of the outer, earlier pseudowavellite, and continue inward toward the center of the nodule, completely crossing the wardite-millisite bands, then crossing an interior shell of dense yellow pseudowavellite and on into the variscite core. Some wardite-millisite shells are separated from the interior dense pseudowavellite by an open space, across which the pseudowavellite veinlets continue, and into which wardite crystals project. These veinlets are very definitely antecedent to the wardite and millisite bands, and to the dense pseudowavellite. The sharp inward protrusions of the alternating bands of wardite and millisite are without doubt controlled by the pseudowavellite veinlets upon which they are centered. Moreover, the dense inner pseudowavellite locally replaces the wardite-millisite bands in irregular protrusions and discontinuous veinlets near their contacts, and thus formed after the wardite and millisite. All the banded material in such structures must have formed by successive centripetal replacement of the original variscite. The sequence of mineralization shown by such specimens is: replacement of the variscite by the pseudowavellite to form the outer shell and, along fractures, to form the small veinlets; alternating replacement, by wardite and millisite, of the new surface of the variscite; some variscite was removed faster than the wardite and millisite were deposited, and into the resulting cavities grew crystals of wardite, some coated by millisite. Then the dense yellow pseudowavellite partially replaced the variscite kernel to form a shell surrounding it, and veining both the wardite-millisite bands and the variscite. This pseudowavellite is of the same generation as that surrounding the isolated spherules of wardite and millisite.

The colloform banding so beautifully developed by wardite and millisite seems not to be a colloidal phenomenon (metacolloid). Although the millisite occurs as fine fibers, the wardite bands are made up of relatively coarse, elongated subparallel grains, many of them terminating in recognizable crystal faces, and upon which grew the succeeding layer of millisite. The only phenomena suggesting an original gelatinous state are the repeated fine banding and the wavy nature of the banding, but

neither of these requires diffusion through a gel (Liesegang rings) for their development. The repeated banding is generally developed on a microscopic scale, but in many specimens outer bands are developed several millimeters thick and made up of well-formed crystals of this order of magnitude which without doubt grew in open spaces. The wavy nature of the banding is commonly controlled by the wavy nature of the surface on which it grew, and the banding is generally not wavy when the surface on which it developed is straight, unless it started as a succession of independent spherules. The banded and spherulitic wardite and millisite must have been deposited from solutions largely by replacement of variscite, and in part in cavities.

Some large specimens are composed in greatest part of wardite. These specimens are cut by crossing thin veinlets of banded pseudowavellite forming an angular boxwork of the whole specimen. The "boxes" formed by the pseudowavellite veinlets are filled mostly with wardite. Parallel and next to the veinlets are alternate bands of wardite and millisite; away from the veinlets the wardite becomes the sole mineral, and occurs in coarse grains. In the center of each "box" is an open space and into this protrude crystals of wardite. Rarely a "box" shows a small kernel of variscite occupying part of its hollow core, and this kernel has a shell of pseudowavellite (in one case, with a thin band of deltaite) around it. Such boxwork specimens must have originated in this way: a variscite nodule was brecciated; in and along the fractures thus developed was deposited a boxwork of pseudowavellite veinlets; later solutions following these veinlets replaced the variscite with wardite and millisite bands parallel to the veinlets; slowly changing solutions stopped depositing millisite and started dissolving variscite faster than they deposited wardite, leaving a cavity to mark the center of each of the former brecciated fragments of variscite; into these cavities grew wardite crystals. The still remaining small variscite kernels were then partially replaced by pseudowavellite. This gives independently a sequence identical with that noted just above.

Other wardite specimens are similarly criss-crossed by pseudowavellite veinlets to form a boxwork; but in these the wardite (and millisite in small amounts) forms large banded spherules partly filling the inter-spaces between the pseudowavellite veinlets. Some of the spherules have their centers on the veinlets, but many complete spherules are supported only on neighboring spherules and the point of support is outward from the center of each. To form thus, the spherules must have started their growth in some supporting medium. It is believed these specimens represent variscite nodules which were brecciated, and the resultant cracks were filled with, and localized the replacement by, pseudowavellite to

form the pseudowavellite boxwork. Spherules of wardite and millisite started to develop in the variscite with their centers randomly placed; with time the variscite was removed faster than the wardite was introduced, leaving an aggregate of spherules, some probably loose, taking the space of the original brecciated fragment. Further introduction of wardite increased the size of the spherules, developed crystal faces on their surfaces, and cemented neighboring spherules together. It is certain that the wardite spherules are later than the pseudowavellite veinlets, and that there was originally a matrix material at least for the pseudowavellite to form in. The pseudowavellite commonly occurs as plates traversing open spaces between spherules; it must originally have had walls to determine its plate-like shape. In some instances where the pseudowavellite veinlet crosses a spherule, the pseudowavellite has been partially replaced leaving only discontinuous elongated patches arranged in line with the unreplaced parts of the veinlet. Variscite is the only mineral which can reasonably be considered as the original matrix material for the spherules, and the original walls for the pseudowavellite veinlets.

One fragment of a nodule is made up of a large mass of white, massive wardite and a massive buff-colored pseudowavellite, and the two are sharply separated by a purplish-brown layer of dense pseudowavellite. The relations of the wardite and pseudowavellite are not shown, nor is anything known of the nature of the nodule from which the fragment came.

Deltaite

Deltaite is nearly as variable in its appearance and manner of occurrence as is pseudowavellite. Five distinct varieties and modes of occurrence were seen by the writer: minute triangular prisms in vitreous pseudowavellite; lavender crystals in cavities; massive lavender bands; dense gray bands; and minute yellow and colorless crystals on pseudowavellite.

In some of the early vitreous pseudowavellite bands and veinlets minute trigonal prisms of deltaite occur intergrown with the pseudowavellite, and evenly distributed through it. It is probable from their occurrence that the two minerals crystallized together. Pseudowavellite and deltaite have been shown in a previous section to be, probably, an isomorphous series, on the basis of Larsen and Shannon's published analyses (1930*b*); it is difficult to conceive how two members of such a series could occur thus intergrown, with sharp non-gradational boundaries. The two minerals are near the two ends of an isomorphous (?) series.

The occurrence of the lavender crystals of deltaite has been described

in the section on Descriptive Mineralogy. This deltaite is later than the outer pseudowavellite shell, and formed after the removal by solution of the original variscite kernel.

Massive bands of fine to medium grained lavender or powder-blue deltaite are optically identical with the lavender crystals. These bands generally occur inside the principal shell of pseudowavellite, and reach a thickness of five or more millimeters. They commonly form the innermost shell, and have crystalline crusts growing upon them extending into the central cavity. Some of these bands are discontinuous and appear to have replaced pseudowavellite, since the same band may change more or less abruptly from deltaite to pseudowavellite, or the deltaite may transect a pseudowavellite band. Although not certain, it seems probable that these deltaite bands followed the deposition of wardite and millisite.

One nodule contains dense gray bands a few millimeters wide, forming crossing veinlets in variscite such that the variscite is in angular to rounded blocks completely surrounded by the gray bands. The gray bands are made up of matted fibers of deltaite ($\omega=1.630$) with repeated thin bands of vitreous wardite in them. The nodule has an outer shell of banded pseudowavellite which must have preceded the formation of the deltaite and pseudowavellite. Dense yellow pseudowavellite occurs as an irregular band in the variscite immediately adjacent to the gray deltaite veinlets; the contact between the pseudowavellite and variscite is gradational, with irregular patches of the pseudowavellite extending into the variscite in a manner requiring replacement as its origin. This deltaite and wardite must have been deposited after the outer shells of pseudowavellite and before the pseudowavellite now seen surrounding the variscite. It thus was introduced at about the time the wardite and millisite were being deposited in other nodules. Apparently some local condition caused deltaite to form instead of the usual millisite.

Minute yellow and colorless crystals of deltaite occur lining cavities between bands of pseudowavellite; in some of these cavities are found small crystals of lewistonite, apparently resting upon the deltaite crystals

Lehiite

Lehiite forms discontinuous dense gray bands and lenses inside the outer pseudowavellite shells. It commonly contains scattered parallel bands of relatively coarse wardite within it. It appears to have the same place in the sequence as the alternating bands of wardite and millisite. In general, the lehiite has formed chiefly by replacement of the variscite after the early pseudowavellite; part may have formed in open spaces, but no open spaces are present now to indicate this. Between the lehiite bands and the variscite cores run thin dense bands of pseudowavellite,

and occasionally coarse gordonite plates. It thus must have formed after the early pseudowavellite and before the inner band of pseudowavellite, separating it from the variscite, and before the gordonite. In one nodule containing lehiite in a large lenticular band, wardite and millisite occur as spherules showing the same time relations as the lehiite: formed after the early pseudowavellite, but surrounded by a later pseudowavellite and gordonite.

Gordonite

Gordonite nearly always occurs as coarse crystals in subparallel groups in the cavities between variscite and the pseudowavellite shells. Thin bands of coarse, subparallel aggregates separate variscite cores from surrounding pseudowavellite. Some fine-grained, platy, green gordonite coats variscite kernels in a thin layer, giving a velvety appearance to the surface.

Occasionally what appear to be single individuals occur in the cavities, and these crystals have a shorter prismatic habit than those occurring in aggregates. Very small single crystals of gordonite occur perched upon the inside walls of some of the granular rough shells of pseudowavellite, surrounding but separated from the variscite kernels. Gordonite has been found only in nodules which still contain variscite, and it is upon or near the variscite that it always forms. Frequently the gordonite crystals are attached to wardite crusts and extend inward toward the variscite kernels.

Bands of coarse plates in subparallel arrangement are present surrounding and replacing variscite kernels immediately inside the white or yellow late crusts of pseudowavellite. These are very similar to bands of montgomeryite surrounding variscite, and like montgomeryite the bands show crystals developed wherever open spaces have been available. The gordonite is thus later than all of the banded pseudowavellite.

Yellow granular oolites of pseudowavellite occur perched upon gordonite crystals and in one specimen have formed pseudomorphs after gordonite. White powdery layers of pseudowavellite likewise coat some of the crystals. In one small nodule a fairly heavy layer of a white amorphous material, probably related to pseudowavellite, fills in around gordonite crystals, and shows shrinkage cracks identical with mud cracks. Members of the apatite group occur as isolated crystals, needles, or aggregates on some of the crystals.

Englishite

Englishite most commonly occurs as subparallel aggregates of plates surrounding spherules of wardite and millisite in variscite; it has replaced

both the wardite and the variscite. Likewise it forms aggregates of plates replacing variscite adjacent to bands of wardite and millisite. In cavities between wardite crusts and variscite kernels it occurs perched upon the wardite as subparallel aggregates of plates in irregular forms several millimeters across. One nodule contains a curved worm-like mass of englishite more than a centimeter long and several millimeters in diameter, growing on a crust of wardite.

Englishite generally occurs in the same nodules with montgomeryite and appears to be the earlier of the two; in one specimen a band of montgomeryite plates has been introduced into the variscite along what must originally have been the contact between a band of englishite plates and variscite. Members of the apatite group occur perched upon englishite in some of the cavities. The relation of englishite to the other crystallized species is not shown.

Englishite must have formed after the bands of pseudowavellite, the wardite and millisite, and the development of the open spaces by solution of the variscite. It is earlier than the montgomeryite and the crystallized apatite members.

Montgomeryite

Montgomeryite most commonly occurs as a thin band, made up of coarse subparallel plates, surrounding and replacing variscite, immediately inside white or dense yellow pseudowavellite. Where these bands project into open spaces, crystals of montgomeryite have developed. Commonly montgomeryite forms a similar thin band in variscite surrounding wardite-millisite spherules. Frequently it is associated with englishite, and has been formed after the englishite as a later band, or as crystals in cavities near englishite masses.

In cavities montgomeryite invariably forms crystals, some up to several millimeters long, and in aggregates a centimeter or more across. It usually forms as subparallel groups. Although it occurs in nodules which contain gordonite, its sequential relation to gordonite is not shown; the two minerals have not been found in contact. It occurs as crystals perched upon wardite crusts, and very commonly on the thin white or yellow separated shells of pseudowavellite near variscite. Occasionally needles and aggregates of apatite minerals and yellow granules of pseudowavellite are found resting upon the montgomeryite crystals.

Overite

Overite is one of the rarest of the minerals in the nodules. In all but one specimen it occurs as coarse to fine crystals growing in cavities upon or near variscite; in one specimen it forms a band of subparallel plates. It is

found growing upon spherulitic shells of pseudowavellite, and isolated or aggregated tiny oolites of nearly white pseudowavellite in turn grow on the overite.

A white fibrous radial group of some apatite member was found upon the tip of one overite crystal. Where overite is massive, it forms a thin shell of subparallel coarse plates between variscite kernels and the encrusting pseudowavellite, similar in occurrence to montgomeryite and gordonite. It is thus later than all the bands of pseudowavellite.

Sterrettite

Sterrettite always occurs as single crystals growing from the walls of irregular cavities in a porous tan-colored pseudowavellite. Associated with it in the cavities are tiny crystals of an apatite mineral; generally the relations of the two are not seen, but occasionally the apatite grows upon sterrettite crystals.

The pseudowavellite containing these crystals is unusual in that none of it has the typical yellow color, but is buff to purplish-brown. The outer shells are very fine grained and compact, while the inner part of the nodules are made up entirely of compactly-grown, platy to fibrous spherulites of pseudowavellite; between the outer shells and the more porous core is commonly an open space, filled in part by loose aggregates of coarse pseudowavellite spherules or by large white spherules of wardite, with little or no millisite. It is in the opening between the outer shells and the core that many of the sterrettite crystals grow, although they can be found scattered through the cores in irregular small cavities.

All of the tan colored pseudowavellite of this type, containing sterrettite, occurred in the deposit in one small area somewhat removed horizontally from the main zone of mineralization. It is in specimens from this one area alone that sterrettite has been found.

Apatite members.

In appearance and optical properties the members of the apatite group are extremely variable. Their habit variation is as follows: (1) balls of radiating fibers or prisms, (2) sheaf-like groups of needles, (3) subparallel aggregates of broad hexagonal prisms, (4) isolated hexagonal prisms, both elongated and stubby, and (5) irregular fibrous aggregates.

With the exception of one form of dehrnite, the apatite members are later than all the minerals closely associated with them in the nodules: they line cavities in pseudowavellite, lehiite, and chert; they are perched upon crystals of wardite, deltaite, gordonite, montgomeryite and sterrettite. The only exception is a shell of radially fibrous dehrnite about two millimeters thick lying between a shell of banded wardite and millisite and an inner shell of dense yellow pseudowavellite; this material seems

definitely to have preceded the inner pseudowavellite. The dehrnite must have formed in an opening between the wardite layer and variscite, since the dehrnite is separated from the wardite by discontinuous lenticular openings.

It seems probable that, in general, the apatite members were the last phase of the mineralization of the nodules. The considerable variation in the types of material deposited in this last phase suggests a complex history; that strictly local conditions were not the principal factor controlling what type of apatite member was deposited is indicated by the fact that as many as three different types occur in the same nodule, and that individual types are frequently zoned.

The detailed sequence of the members within this group has not been determined since the chemistry of the various types is incompletely known. Most of the types are present in quantities far too small for chemical analysis.

SEQUENCE OF MINERALS

The sequence of deposition of the phosphate minerals has for the most part been definitely determined.

Variscite without doubt was the original phosphate mineral to be deposited; in itself it represents a complete stage of deposition, and shows no alternations or gradational sequence with any other mineral: all of the variscite was deposited before any other phosphate started to form.

Pseudowavellite was the second mineral to form in the nodules, and represents here a centripetal replacement of the original variscite. Accompanying the earliest pseudowavellite was a small amount of deltaite.

Millisite and wardite directly follow pseudowavellite in the sequence. The two were alternately deposited as successive bands or shells; most of the millisite is earlier than most of the wardite, although wardite accompanied the earliest millisite, and millisite accompanied the latest wardite. The earlier material all represents replacement of variscite, while much of the later wardite was deposited in open spaces.

Lenticular crusts of dennisonite containing thin bands of wardite, and veins and bands of gray deltaite containing thin bands of wardite occupy positions in the sequence identical with millisite; no two of the three types ever occur in contact in the same nodules so that their relative sequence cannot be told. Since they are all interbanded with wardite, it may be that they all formed simultaneously, local conditions determining which was to deposit.

Following the wardite (and gray deltaite and lehiite) is a recurrence of pseudowavellite, forming compact yellow and white layers surrounding the remaining variscite. Most of this material is likewise a replacement of the variscite.

In one nodule, a band of dehrnite, deposited in part in openings, must have formed between the wardite and the second pseudowavellite periods.

Some deltaite, particularly the massive lavender material, either accompanied the second stage of pseudowavellite, or followed it by replacement; the crystalline deltaite must have formed at this same time.

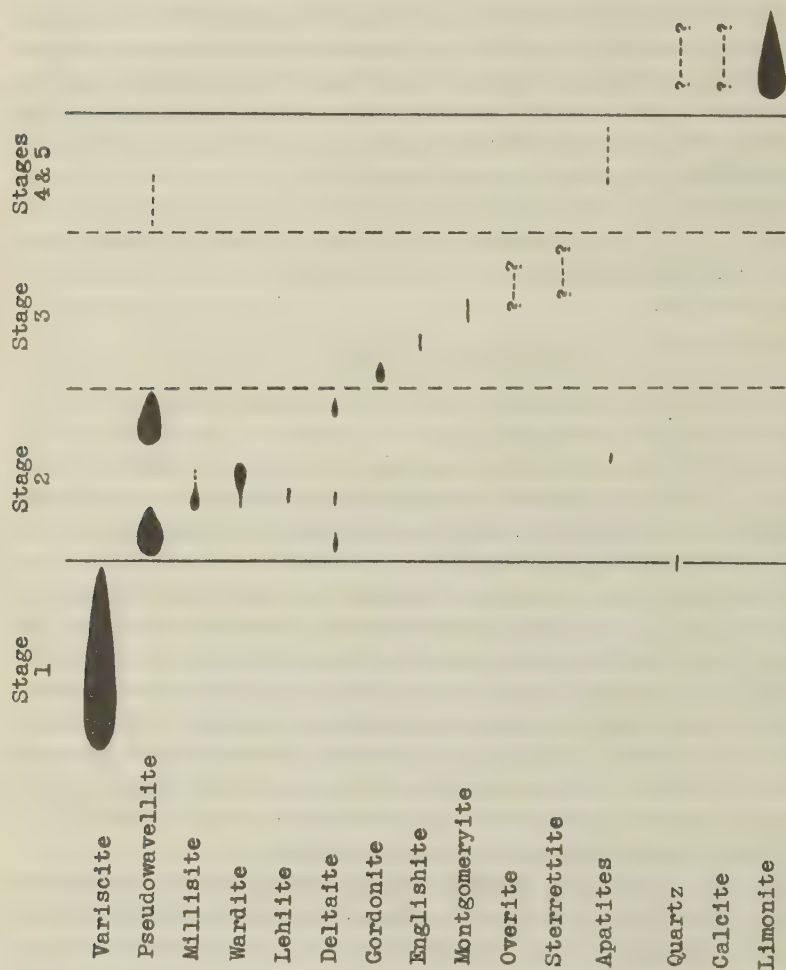


FIG. 4. Tabular view of the sequence of mineralization.

The minerals following the second pseudowavellite stage commonly occur as crystals in cavities of the preceding minerals. The mutual relations of the minerals of this group are poorly known since the minerals are rare and when found are not ordinarily accompanied by other members of the same group. Certain relations are shown however: englishite

is earlier than montgomeryite, and probably follows gordonite; the apatite minerals are later than the other crystallized minerals. Overite and sterrettite have not been found with crystalline types other than the apatite members, so they remain unplaced in the sequence of this group.

Isolated oolites of yellow to white pseudowavellite were deposited after and upon the crystal-forming minerals, with the exception of the apatite members; at least some of the apatite minerals were later than these pseudowavellite oolites.

Figure 4 gives a tabulation of the sequence. Five distinct stages are represented: (1) the original variscite; (2) the banded minerals which replaced and enclosed the variscite; (3) the crystal-forming minerals in cavities of the earlier minerals; (4) the minor reversion to pseudowavellite; (5) members of the apatite group, overlapping perhaps with (4).

Minerals other than phosphates associated with the nodules are in most part either earlier or later than the phosphates. The one exception to this is the fine-grained quartz which occurs as tiny black veinlets in the variscite, and along which the banded pseudowavellite has formed; this quartz represents the first mineral to form after variscite.

Alunite and chert preceded the phosphates, and are probably genetically unrelated to them. Limonite is very probably later than the phosphates. Late calcite and quartz in tiny seams and crystalline coatings are later than any of the phosphates and the limonite.

CHEMICAL SEQUENCE

The mineralogical sequence has been shown to represent five distinct stages of solution activity. Each of the stages displays unique chemical qualities.

Stage 1. The primary stage is the deposition of variscite. Mineralogically this is simple and represents the deposition, from moving phosphate-bearing waters, of a normal hydrous aluminum phosphate— $\text{Al}(\text{PO}_4) \cdot 2\text{H}_2\text{O}$. No other material was deposited at this stage.

Stage 2. This period represents an alteration of the variscite, an alteration which was largely a readjustment of the original aluminum phosphate and the introduction of CaO, rather than a bulk replacement of the variscite by entirely new material. During this time hydrous basic phosphates of aluminum and calcium, together with some sodium, encroached upon the variscite. The chief minerals of this stage, pseudowavellite, wardite, and millisite, have an atomic ratio $\text{Al}:\text{P}$ (or PO_4) = 3:2. The time sequence of all the minerals of the stage closely parallels an increase in the atomic ratio of $\text{Na}:\text{Ca}$, with a reversion at the end. The following tabulation demonstrates this fact:

			Na:Ca
<i>Early</i>	Pseudowavellite	$\text{CaAl}_3(\text{PO}_4)_2(\text{OH})_5 \cdot \text{H}_2\text{O}$	0:1
	(Deltaite)	$\text{Ca}_2\text{Al}_2(\text{PO}_4)_2(\text{OH})_4 \cdot \text{H}_2\text{O}$	0:1
	(Lehiite)	$\text{Ca}_6\text{Na}_2\text{Al}_8(\text{PO}_4)_8(\text{OH})_{12} \cdot 6\text{H}_2\text{O}$	2:5
	Millisite	$\text{Ca}_2\text{Na}_2\text{Al}_{12}(\text{PO}_4)_8(\text{OH})_{18} \cdot 8\text{H}_2\text{O}$	1:1
	Wardite	$\text{CaNa}_4\text{Al}_{12}(\text{PO}_4)_8(\text{OH})_{18} \cdot 8\text{H}_2\text{O}$	4:1
	Pseudowavellite	$\text{CaAl}_3(\text{PO}_4)_2(\text{OH})_5 \cdot \text{H}_2\text{O}$	0:1
<i>Late</i>	Deltaite	$\text{Ca}_2\text{Al}_2(\text{PO}_4)_2(\text{OH})_4 \cdot \text{H}_2\text{O}$	0:1

Although millisite and wardite were deposited alternately, the bulk of the millisite crystallized before the bulk of the wardite.

The minerals of this group are the most basic of the series; the ratio of $\text{PO}_4:\text{OH}$ is approximately 2:5, as compared to 1:1 in the third group. This is the principal group in which alkalis are important. Dehrnite occupies an anomalous position late in this group.

Stage 3. Although the actual sequence of the minerals in this group could not be definitely established, the minerals as a whole show certain distinct chemical characteristics. The atomic ratio of $\text{Al}:\text{P}$ (or PO_4) is approximately 1:1 in all cases, a decrease in the relative amount of Al from stage 2. The minerals of this group are all basic, the ratio of the radicals $(\text{PO}_4):(\text{OH})$ approximating 1:1; this is a marked decrease in hydroxyl content from stage 2. The water of crystallization is somewhat higher in stage 3, so that the total water for the minerals of both groups is about the same.

Gordonite occupies a rather anomalous position in this mineral association. It is the only mineral in the deposit in which MgO is dominant, yet it was apparently formed in the same stage with minerals containing no determinable MgO . The minerals of the preceding and succeeding stages all contain MgO as a minor constituent (analyses, Larsen and Shannon, 1930*b*). Although there is no evidence from its occurrence, gordonite might be considered as having formed in a stage of deposition intermediate between stages 2 and 3. It is by far the most abundant of the stage 3 minerals.

Stage 4. This period represents a reversion to early conditions with the deposition of minor amounts of pseudowavellite, which was apparently deposited from solution rather than being a reaction product of the variscite. Part is certainly earlier than the apatite group, but some may be later.

Stage 5. This stage is represented solely by minerals belonging to the apatite group. Although analyses are not available for most of the minerals of the group, it can be said with some certainty that they are characterized by the absence of essential Al_2O_3 . From the analyses available (Larsen and Shannon, 1930*b*) it seems that the variation within the group is in the relative quantities of Na_2O , K_2O , CaO , and MgO and, to some

extent, H_2O and CO_2 . What the sequence of this variation may be is not known. There were probably several periods of crystallization within this stage since two or more members occur together in the same nodule.

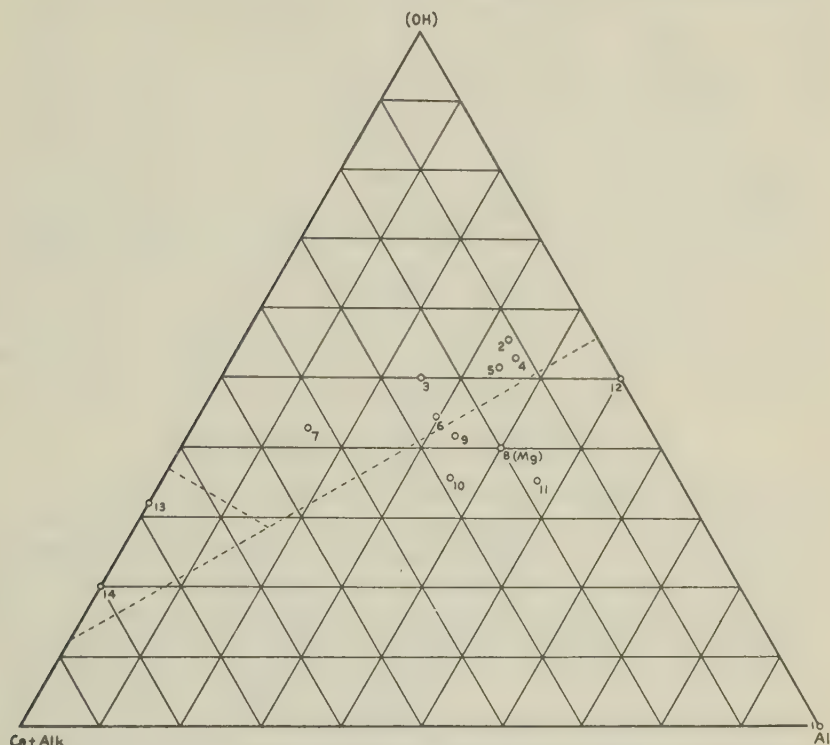


FIG. 5. Ternary diagram on which is plotted the atomic ratios $\text{Ca} + \text{alkalies} : \text{Al} : \text{OH}$ of the analyzed minerals from the nodules. 1 variscite, 2 pseudowavellite, 3 deltaite, 4 millisite, 5 wardite, 6 lehiite, 7 dennisonite, 8 gordonite, 9 englishite, 10 montgomeryite, 11 overite, 12 sterrettite, 13 lewistonite, 14 dehrnite.

The chemical characteristics of the stages can be seen in Figs. 5 and 6. In Fig. 5, the ratio $\text{Ca} + \text{alkalies} : \text{Al} : \text{OH}$ is plotted for each phosphate mineral found in the deposit; the points above the broken line (more basic minerals) represent only minerals formed in stage 2; those below the line are stage 3 minerals (with the exception of variscite). Figure 6 shows the ratios of $\text{Ca} + \text{alkalies} : \text{Al} : \text{PO}_4$ of the same minerals; in this the dotted line likewise divides stage 2 from stage 3 minerals. In both diagrams, the two analyzed apatite minerals (stage 5) are isolated to the left, the only minerals free of essential Al_2O_3 .

Limonite was apparently the last to be deposited in abundance, and

would seem to have no genetic relation to the minerals of the nodules. It has not replaced or altered any of the phosphates, and is not included in any of the nodules.

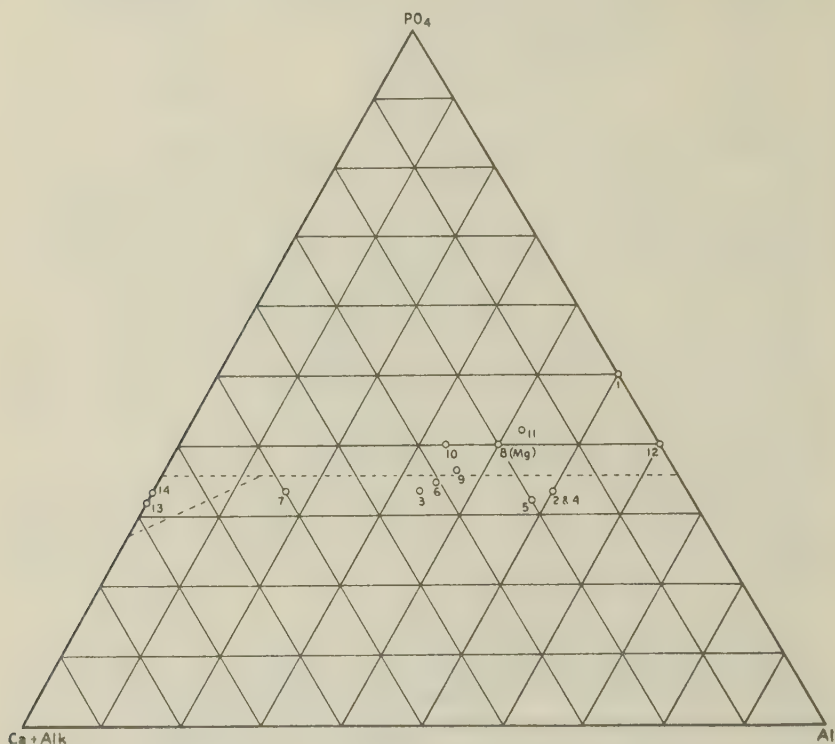


FIG. 6. Ternary diagram on which is plotted the atomic ratios $\text{Ca}+\text{alkalies}:\text{Al}:\text{PO}_4$ of the analyzed minerals from the nodules. 1 variscite, 2 pseudowavellite, 3 deltaite, 4 millsite, 5 wardite, 6 lehiite, 7 dennisonite, 8 gordonite, 9 englishite, 10 montgomeryite, 11 overite, 12 sterrettite, 13 lewistonite, 14 dehrnite.

In the discussion of these stages of deposition, no recognition has been given to the presence of quartz or calcite in the nodules. Calcite is not common in the nodules, although it is common on their outer surfaces. Where it formed it was definitely later than the banded vuggy material containing it; most of it is probably later than all the phosphates. The fine seams of quartz associated with some of the veins of pseudowavellite formed during the phosphate period. They are believed to be an intermediate and brief interlude in the sequence of the phosphates, and were probably associated in some way with the movements which fractured the variscite and preceded stage 2.

PERIODS OF PHOSPHATE DEPOSITION

It has been shown that the variscite was the first mineral to be deposited, and that the principal later minerals formed by alteration and replacement of the variscite. It seems, therefore, that two major periods of mineralization can be postulated: the first period represents the deposition of variscite from phosphate-bearing solutions; the second period represents primarily an alteration of the original variscite, and not the introduction of new phosphate material, since the alteration minerals are found associated only with variscite or where variscite must originally have been. Thus the solutions which deposited the variscite need have no relation in time to the solutions responsible for the alteration minerals. Actually a time interval between the two periods is indicated by the fact that after all of the variscite had been deposited, movements causing brecciation and fracturing of the variscite took place, and this preceded all of the secondary phosphates; the length of the interval between the two periods is not indicated, but need not have been long.

STRUCTURAL HISTORY OF THE NODULES

A cursory examination of many of the nodules suggests several periods of fracturing, or movement along pre-existing fractures, during the development of the secondary phosphates. Many structures appear to be offset: wardite-millisite spherulites and bands do not meet on opposite sides of a fracture; white pseudowavellite areas are in contact with variscite along sharp straight breaks; inner bands of pseudowavellite appear offset against veinlets of pseudowavellite.

When studied in detail, it is necessary to conclude that only one period of fracturing and movement occurred during the phosphate mineralization, and that this took place after the formation of the variscite and before any of the alteration products. There is no doubt that the outer shell of pseudowavellite was the first mineral to replace the variscite, and these outer shells are always intact. Moreover, the veins of pseudowavellite crossing the nodules have banding continuous with the banding of the outer shell, and thus were formed simultaneously with the outer shell; these are not displaced or offset by fracturing. Many fractured nodules have a continuous outer pseudowavellite shell separated from the variscite core by a wide, almost continuous cavity; the rounded core is made up of angular blocks of variscite in contact with angular blocks of white or yellow pseudowavellite, and of banded wardite and millisite in variscite. Here again the minerals occurring with variscite in the core are later than the unfractured pseudowavellite shell, and in part later than the surrounding cavity; they must have replaced brecciated variscite selec-

tively to retain the brecciated structure. It would be impossible for shearing stresses to have fractured the core without first crushing the outer shell. It is thus an antecedent breccia: the breccia was formed before the minerals that now comprise the breccia fragments.

The structural history then is simple: following the formation of the variscite nodules, minor to extreme brecciation occurred; the replacement of the variscite was in part guided by these fractures to produce pseudomorphs after the original structures. No other fracturing or movement occurred.

(To be continued)

THE ALTERATION PRODUCTS OF OLIVINE AND LEUCITE IN THE LEUCITE-LAMPROITES FROM THE WEST KIMBERLEY AREA, WESTERN AUSTRALIA

REX T. PRIDER AND W. F. COLE,

University of Western Australia, Nedlands, Western Australia.

ABSTRACT

The leucite in the West Kimberley lamproites is largely replaced by a turbid substance. An x -ray, optical and chemical examination of such altered phenocrystal leucite indicates that the leucite has been replaced by an aggregate of orthoclase and an unidentified clay-like mineral. Olivine has been replaced by nontronite. The petrogenetical significance of the results is discussed.

INTRODUCTION

The leucite lamproites of the West Kimberley Area (Wade and Prider, 1940) are composed essentially of leucite associated with phlogopite, diopside, and magnophorite. Chemically their main features are a high potash content (in excess of alumina) and a silica content sufficient to have developed orthoclase, instead of leucite. Some unusual minerals from these rocks have been previously described (Prider, 1939). It was noted in this paper (p. 385) that the leucite is rarely fresh but replaced largely by a turbid clay-like mineral which, in view of the high potash content and silica saturated nature of the rocks, was thought to contain much more silica than leucite and also, in spite of its clayey appearance, still to contain considerable potash.

Insufficient material was available at that time to attempt any separation of the leucitic material, but a considerable amount of a lamproite from "P" Hill with leucite phenocrysts up to 1 mm. in diameter was obtained by one of us (R. T. P.) in 1939, and about half a gram of altered leucite was obtained by drilling the phenocrystal leucite with a dental drill. A partial chemical analysis and an optical and x -ray examination were made of this material and the results are described below. This same rock (from "P" Hill) contains a notable amount of olivine completely pseudomorphed by a fibrous, greenish mineral which was considered in the previous paper (Prider, 1939, p. 386) to be possibly nontronite. A sufficient amount of this material was obtained to enable an x -ray examination to be made. The powder representing the pseudomorphs after leucite may possibly contain a little of this greenish mineral as the altered olivines are often very close to the leucite phenocrysts, and in the same way the powder from the olivine pseudomorphs may be slightly contaminated by the leucitic alteration product.

The x -ray investigation of these materials was carried out by the pow-

der method of analysis. The technique employed and the general experimental procedure have been previously described (Shearer and Cole, 1940; Cole, 1941). In the examination of these samples it was found convenient to use Cu radiation filtered, so as to reduce the K_{β} component, by a 10μ thick nickel filter previously prepared by electro-deposition (Shearer and Cole, 1940).

The interplanar spacings were calculated directly from the Bragg equation on the basis of a constant camera radius of 2.798 cms. This was rendered possible by the fact that in this and previous work a camera of uniform radius was employed and it was shown (Cole, 1941) that the assumption of a uniform radius of 2.798 cms. for this camera yields results in which the total maximum percentage error for the strongest lines is 1.42 to 0.16 over the range 10\AA to 1\AA , on the assumption that (a) the radius along the film is uniform, and (b) $d(2s)$ is 0.1 mm. in measurement of a line (where $2s$ is the separation of corresponding diffraction lines along the film in the equatorial plane).

In this work the materials examined contained no immediately recognizable standard substances from which calibrations of the films could be made, but it is believed that the assumption of a constant radius of 2.798 cms. yields results of the same order of accuracy as that obtained in previous investigations. As detailed below, calcite is a constituent of the leucite alteration product and the occurrence of a spotted line in the diffraction pattern of this material at 3.05\AA , identified as the prominent 3.03\AA calcite spacing, supports this contention.

THE ALTERATION PRODUCT OF OLIVINE

This material is greenish in colour, micaceous in habit, and completely replaces euhedral olivine (Wade and Prider, 1940, p. 67 and Fig. 7B). The optical properties of this mineral (Prider, 1939, p. 386) are: X =yellow green, $Y=Z$ =bright green; absorption $X<Y=Z$. $N_g=1.625$, $N_p=1.595$, $N_g-N_p=0.030$. The fibers are length slow. These characters indicate that the mineral is probably nontronite. Slices of the rock from "P" Hill were stained with malachite green without any preliminary acid treatment and the stain was strongly absorbed by this material (Fig. 1), thus supporting its determination as a clay mineral.

The x-ray powder photograph of this material gives the interplanar spacings as tabulated in Table 2, where the assigned origin of each line is also indicated. In preparing this and subsequent tables the principle was employed of assigning an origin to a line only when, on intensity considerations, the line was likely to be contributed to by the mineral in question. Data concerning the montmorillonite group of minerals were taken from Nagelschmidt (1938) and Kelley *et al.* (1939), and similar informa-

tion regarding the mica group of minerals was obtained from Nagelschmidt (1937). These publications include only data to which Miller indices related to a definite unit cell could be assigned.

Advantage was also taken of the fact that upon heating members of the montmorillonite group of clay minerals to 500° C. the characteristic 15Å basal spacing of air-dried material shrinks to 10Å. Members of the mica group are unaffected by such treatment. Heat treated material of the olivine alteration product showed this contraction and this further strengthens the conclusion arrived at from a consideration of the pattern as a whole that a clay mineral of the montmorillonite group is the predominant mineral in this sample.

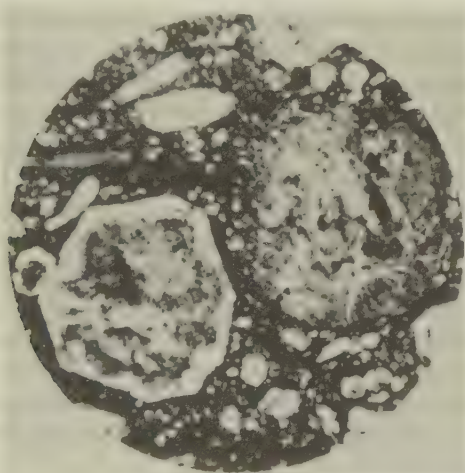


Photo by H. J. Smith

FIG. 1. Photomicrograph of the lamproite from "P" Hill, West Kimberley. The field of view shows phenocrysts of altered leucite and olivine together with several smaller phenocrysts of diopside (upper left). The groundmass of the rock consists of a brownish turbid material in which are set many small leucite and rutile crystals. The section has been stained with malachite green and as a result the central turbid clayey portions of the leucite phenocrysts (lower left) appear blue. The stain has affected the nontronite pseudomorph after olivine (middle right) in such a manner that the outer margins appear purple and the darker coloured central parts green. Ordinary light, $\times 45$.

Optical evidence (as above) indicates that the mineral of the montmorillonite group is nontronite, and similar evidence suggests that the mica group mineral is phlogopite (the pseudomorphs after olivine are often rimmed with phlogopite (Wade and Prider, 1940, p. 67)). No residual olivine was seen under the microscope and in considering the origin of lines tabulated in Table 2 for the olivine alteration product, this con-

stituent has not been considered. *X*-ray data yield very little evidence for the existence of any constituent other than those already considered.

The final *x*-ray conclusions regarding the constituents of the alteration product of the olivine are summarized in Table 4, in which all estimates of relative quantities are based on visual observation of line intensities.

THE ALTERATION PRODUCTS OF THE LEUCITE

(a) *Microscopic examination and chemical analysis.* The leucite in most of the lamproites from the West Kimberley area is altered, as has been noted, to a turbid clayey substance. In the rock from "P" Hill the leucite phenocrysts, in addition to the clayey alteration, are partly replaced by a weakly birefringent colourless mineral occurring in small rude spherules with their centers on the edges of the original leucite phenocrysts. This is the only rock from which a reasonably pure sample of altered leucite could be obtained by drilling the phenocrysts, and it was this material that was subjected to chemical and *x*-ray analysis. The usual alteration is however generally more turbid and contains very little of the colourless weakly birefringent material.

A description of the "P" Hill rock has been given previously (Wade and Prider, 1940, p. 70) and it was noted here that "the leucites are all perfectly shaped, clearer than usual and are partly replaced, especially on their outer margins, by a colourless, weakly birefringent spherulitic zeolite, with $N=1.508$." In the group of specimens from which the material at present under examination was obtained, the leucites appear to be similar to the description given above because the outer zones are replaced by a weakly birefringent material and the central parts by turbid clayey material (Fig. 1).

The *x*-ray analysis indicates the presence of feldspar and accordingly, a closer examination of the clear mineral was made. This material, quoted previously as having a refractive index of 1.508, is seen to consist of two substances: (1) a clear isotropic mineral with $N=1.508$, and (2) the weakly birefringent material with refractive index approximately 1.520 (orthoclase).

Staining tests were made on slices of this rock as follows:

(1) A section was stained with malachite green without any preliminary acid treatment, with the result that the central turbid parts of the leucite phenocrysts retained the stain (Fig. 1), behaving in this respect like a clay mineral.

(2) A section fumed with HCl and then stained with malachite green yielded the same result. A similar result was obtained by staining after the direct application of HCl to the rock surface. These tests indicate that the outer comparatively clear zone of the phenocrysts, which did

not retain the stain, is composed neither of leucite nor of a zeolite.

(3) A section was fumed with HF and stained with sodium cobaltinitrite (after the method suggested by Keith, 1939, for staining potash feldspar) with the result that the clear portions retained the yellow stain, behaving in this respect like potash feldspar (in view of the absence of leucite or a potash bearing zeolite—see (2) above). It may be noted here that the groundmass of the rock also retained the yellow stain, indicative of the presence of potash.

In the sample which was drilled from the leucite phenocrysts and subsequently used for chemical and x-ray analyses, orthoclase (see above) and an isotropic clayey mineral with $N=1.508$ (? cimolite) were the most abundant minerals identified. Mica (?), nontronite, diopside, and calcite were the only minor constituents recognized. Mica (?) occurs as occasional pale greenish rod-like forms scattered through the clayey mineral. These tiny rods have straight extinction, positive elongation, marked birefringence, and refractive index >1.581 . Nontronite is rare and apparently has been derived from altered olivine which in places is closely associated with altered leucite. Diopside occurs as rare stout prisms. It has evidently come from inclusions in the original leucite phenocrysts or from the immediate vicinity of such phenocrysts. The more or less simultaneous crystallization of leucite and diopside in these rocks has been noted (Wade and Prider, 1940, p. 87). Calcite is in the form of tiny granules which effervesce readily in cold acid. None of this mineral could be detected in the thin slices and it seems probable that an occasional small amygdale (indistinguishable in hand specimen from a leucite phenocryst) has contributed this constituent.

TABLE 1. CHEMICAL ANALYSIS OF THE ALTERATION PRODUCTS OF LEUCITE

SiO ₂	52.63
Al ₂ O ₃	19.75
Fe ₂ O ₃	4.68
TiO ₂	1.54
CaO	2.38
MgO	3.40
¹ H ₂ O+(+CO ₂)	5.98
H ₂ O—	2.70
BaO	3.86
² K ₂ O(+Na ₂ O)	3.08
	100.00

¹ Loss on ignition of material dried at 110°C.

² By difference. It is considered, in view of the abundance of K₂O and absence of Na₂O from the analysis of a rock from "P" Hill (Skeats, 1926, p. 43), that this is entirely K₂O.

Analyst R. T. Prider.

The chemical analysis of the alteration products of the leucite (containing the above constituents) is given in Table 1. As only 0.30 gm. of material was available, the CO_2 content could not be determined and the alkalies could only be estimated by difference.

(b) *X-ray examination.* The interplanar spacings of the leucite alteration products are tabulated in Table 2 (for the material both before and after heat treatment at 500°C.) together with the assigned origin of each line. In drawing up this table, data additional to that already quoted were necessary and these were obtained from Mehmehl (1939), Norton (1939), and Hanawalt, Rinn and Frevel (1938). In considering the presence of calcite, reference was made to the data supplied by Nagelschmidt (1934).

From an examination of Table 2 it is apparent that the sample contains a small amount of two clay minerals, one belonging to the montmorillonite and the other to the mica group. This evidence is obtained from a consideration of the characteristic basal spacings of these two groups, viz. a 15\AA spacing of montmorillonite which shrinks to 10\AA on heating to 500°C. , and a 10\AA mica spacing which is unaffected by heat treatment.

The conclusion that potash feldspar is present, rather than leucite, is obtained from a consideration of the patterns characteristic of these two minerals. At the commencement of this work no data regarding leucite were known to the authors and a single crystal of leucite (from Albano, Italy) was therefore crushed and its powder diffraction pattern obtained. This pattern is given in Table 3 from which it can be seen that the strongest leucite lines occur at 5.33, 3.42, 3.24, 2.88, 2.80, 2.35 and 1.65\AA . The strongest lines of orthoclase occur at 3.20, 2.87 and 1.778\AA (Norton, 1939). The absence of a line at 5.33\AA and the occurrence of only a weak line at 3.40\AA in the diffraction pattern of the leucite alteration products has led to the above conclusion.

The presence of calcite is indicated by a spotted line at 3.05\AA . This line does not appear after heat treatment, even though material which did not enter the container showed the presence of a small amount of carbonate when treated with HCl. Kelley *et al* (1941) have recently noted the tendency for calcite to decompose on heating to 500°C. in the presence of a clay mineral and the above observation supports this conclusion. It is noteworthy that the intensity of the lines assigned to feldspar generally increases after a heat treatment.

Chemical and microscopic evidence indicates a small amount of rutile, but as the strongest line of this material occurs at 3.24\AA (Kelley *et al* 1939) coincident with the strongest feldspar line, no conclusion, from the x-ray diffraction pattern, has been reached as regards its presence in the sample examined. There is very little evidence for the presence of any of

the oxides or hydroxides of aluminum or iron. The significance of the possible presence of candle grease in the pattern has been referred to in a previous publication (Cole, 1941).

TABLE 2. INTERPLANAR SPACINGS OF THE ALTERATION PRODUCTS OF OLIVINE AND LEUCITE IN THE WEST KIMBERLEY LEUCITE LAMPROITES

Alteration of Olivine			Alteration of Leucite					
Unheated			Unheated			Heated to 500°C.		
Possible origin	Intensity	<i>d/n</i>	Possible origin	Intensity	<i>d/n</i>	Intensity	<i>d/n</i>	
Mo	vs	15.39 ²	Mo	w-m	14.87			
Mi	m	9.92	Mo(Mi)	?	10.15	m	9.92	
MoMi	vw	4.91	U	m	8.05	m	7.91	
MoMi	s	4.46	U	m	7.07	m	7.07	
(Mi)	vw	3.62	U	m	6.30	m	6.34	
Mi	w	3.29	Mo(Mi)	w(d)	5.09	vw	5.09	
Mo	vw	3.07	Mo(Mi)				4.50	
MoMi	s	2.57	FCg	m	{4.22	m	{4.24	
Mo	w	2.394	FCg	w	{3.97		{3.96	
Mi	d	2.172	FCg	w	3.72	m	3.74	
Mi	?	1.970	U	vw	3.53	vw	3.57	
MoMi	vw	1.671	F(Mi)	vw	3.39	vw	3.40	
MoMi	s	1.510	F	ms	{3.27	s	3.25	
Mo(Mi)	w	1.301	C	m	{3.05 ¹			
			MoF	m	2.93	ms	2.95	
			MoF(Mi)	m(d)	{2.72	w	2.72	
			(F)		{2.52	ms	2.56	
						vw	2.381	
			F(Mi)	vw	2.142		{2.199	
			U	m	2.088	w	{2.143	
			U	vw	2.039		{2.088	
			(F)(Mi)	vw(d)	1.932	vw	1.902	
			(F)	w	1.843	w	1.840	
			F	w	1.779	w	1.782	
			U			vw	1.745	
			Mo	w	1.702	vw	1.696	
			U(Mi)	w	1.658	w	1.658	
			U			?	1.596	
			(F)	vw	1.578	vw	1.578	
			MoF(Mi)	w	{1.517	w	{1.522	
			F	vw(d)	1.484		{1.486	
			(F)		1.421	w	1.421	
			U	vw(d)	1.356	vw	1.396	
			U	?	1.314			
			FMo			vw(d)	1.287	
			(F)Mo			vw	1.248	
			(F)			vw	1.205	
			U			vw	1.170	

vs=very strong; s=strong; ms=medium strong; m=medium; w=weak; vw=very weak; d=diffuse.

Mo=Montmorillonite; Mi=Mica; F=Feldspar; C=Calcite; Cg=Candle grease; U=Unidentified.

¹ A spotted line.

² This line shrinks to 10.0 Å after heating to 500°C.

As will be seen from Table 2 the authors have not been able to assign an origin to quite a number of lines in the pattern, in particular to those occurring at approximately 8.0, 7.07 and 6.30Å. In soil colloid work a

TABLE 3. X-RAY DIFFRACTION PATTERNS OF LEUCITE (FROM ALBANO, ITALY) AND DIOPSIDE (FROM "P" HILL, WEST KIMBERLEY AREA, W.A.)

Leucite		Diopside	
Intensity	<i>d/n</i>	Intensity	<i>d/n</i>
w	9.25	w	4.03
vw	5.95	vw	3.65
vs	5.33	w	3.28
w	4.68	m	3.16
vw	4.16	s	2.95
w	3.77	w	2.89
w	3.57	w	2.86
vs	3.42	s	2.53
vs	3.24		2.485
vw	3.05	w	2.275
s	2.88	w	2.187
s	2.80	w(b)	2.108
m	2.61		2.017
vw	2.453	w	1.991
s	2.352	vw	1.953
vw	2.287	?	1.887
m	2.118	vw	1.843
w	2.044	w	1.818
vw	1.995	?	1.790
w	1.905	w	1.738
w	1.843	vw	1.658
w	1.773	m	1.615
m	1.714	vw	1.578
s	1.652	vw	1.543
w	1.615	w	1.517
w	1.570	w	1.497
w	1.520	vw	1.477
m	1.469	m	1.414
vw	1.431	w	1.402
vw	1.401	w	1.322
w	1.369	w	1.279
vw	1.346	w	1.259
w	1.314	w	1.244
w	1.296	vw	1.209
	1.285	vw	1.170
vw	1.268	vw	1.144
m	1.240	?	1.102
vw	1.198	m	1.068

vs=very strong; s=strong; m=medium; w=weak; vw=very weak; b=broad.

7.0Å line normally indicates the presence of a member of the kaolinite group. However, this line is removed with the remainder of the kaolinite pattern when kaolinite bearing samples are heated to 500° C. The continued existence of the 7.07Å spacing in the leucite alteration products after heating clearly indicates the absence of kaolinite.

The only other minerals likely to be present and known to the authors to possess a 7Å spacing are the serpentines. Gruner (1937) quotes data for chrysotiles in which the strongest lines occur at 7.908, 7.118, 4.457, 3.588, 2.573, 2.421, 1.519 and 1.297Å. Most of these lines can be fitted into the pattern obtained from the leucite alteration products but the paragenesis of the serpentines and the chemical analysis seem to negative any possibility of the presence of any appreciable quantity of serpentine in this sample.

Occasional prisms of diopside were noted in the sample when examined microscopically. These do not appear to have produced any lines in the pattern. The pattern obtained from diopside separated from the "P" Hill rock is given in Table 3.

The composition of the alteration products of leucite as determined from the *x*-ray examination is given in Table 4.

(c) *Discussion of results:* In the light of the *x*-ray and microscopical examination of the leucite alteration products, the chemical analysis has been recast in terms of the minerals present and the result is shown in Table 5.

In this calculation it has been assumed that the K₂O and BaO are all contained in the feldspar and all the CaO is in calcite and diopside. In the absence of a knowledge of the CO₂ content, microscopic evidence suggesting that calcite is somewhat more abundant than diopside has been taken into account in determining the relative amounts of calcite and diopside.

The nontronite (= nontronite + Mg-beidellite) shown in the calculation as amounting to 21.6% is far in excess of nontronite which could be contributed by olivine and which was observed in the powder from the leucite, so it is probable that some iron and magnesia are present in the residue. The residue (which is apparently the material giving the unknown lines in the *x*-ray diffraction pattern) in the above calculation amounts to 40 per cent and consists essentially of silica, alumina, and an unknown amount of water (unknown in view of the fact that the water that should be assigned to nontronite and Mg-beidellite is not exactly known). This gives Al₂O₃:SiO₂: : 1:3 so that this unknown material (if it be a single mineral) may be Al₂O₃ · 3SiO₂ · *x*H₂O with the possibility of Mg and Fe entering its composition from the material calculated as nontronite (which as noted above is far in excess of nontronite observed under the microscope).

PETROGENETICAL SIGNIFICANCE OF THE INVESTIGATION

It has been shown that in the pseudomorphs after leucite there are no remnants of the original leucite, but the pseudomorphs consist of a num-

TABLE 4. COMPOSITION OF THE ALTERATION PRODUCTS OF OLIVINE AND LEUCITE IN THE LAMPROITE FROM "P" HILL AS DETERMINED BY X-RAY ANALYSIS

Mineral	Olivine pseudomorphs	Leucite pseudomorphs
Montmorillonite group	Much	Little
Mica group	Little	Possible trace
Feldspar	—	Much
Calcite	—	Very little
Unknown	—	Much

ber of minerals including orthoclase, a montmorillonite group mineral (which may be montmorillonite derived from leucite or nontronite from olivine introduced into the powder while drilling the leucite phenocrysts,

TABLE 5. CALCULATION OF THE MINERALS PRESENT IN THE PSEUDOMORPHS AFTER LEUCITE

	%	Mol. Props.	Rutile	Orthoclase	Celsian	Calcite	Diopside	Nontronite	Mg-Beidelite	Residue
SiO ₂	52.63	877	—	198	52	—	20	116	100	391
Al ₂ O ₃	19.75	193	—	33	26	—	—	—	—	134
Fe ₂ O ₃	4.68	29	—	—	—	—	—	29	—	—
TiO ₂	1.54	19	19	—	—	—	—	—	—	—
CaO	2.38	43	—	—	—	33	10	—	—	—
MgO	3.40	85	—	—	—	—	10	—	75	—
H ₂ O + {CO ₂ 1.45}	33	—	—	—	—	33	—	—	—	—
{H ₂ O + 4.53}	5.98	252	—	—	—	—	—	29	25	198
H ₂ O —	2.70	—	—	—	—	—	—	—	—	—
BaO	3.86	26	—	—	26	—	—	—	—	—
K ₂ O	3.08	33	—	33	—	—	—	—	—	—
	100.00		1.54%	18.35%	8.20%	3.30%	2.16%	12.16%	9.45%	40.73%
				26.55% Hyalophane				21.61% Nontronite		

¹ For the purpose of this calculation it has been assumed (see text) that the 5.98% loss on ignition consists of 1.45% CO₂ and 4.53% H₂O.

as indicated in the introduction, and an unknown mineral (or minerals). The orthoclase content of the pseudomorphs is probably higher than that of the powder examined as the orthoclase tends to be confined to the outer zones of the original leucite, and in boring the leucites there is a tendency to have the more central parts concentrated in the resultant powder.

The petrological interest lies in the fact that in this rock there has been

a considerable reaction of the early formed leucites with the siliceous residuum to form orthoclase, and this accounts to some extent for the silica saturated nature of these rocks and also gives further information regarding the temperature of final crystallization of these rocks which must have been at, or slightly lower than, the leucite-orthoclase reaction temperature.

The more general alteration of leucite is, however, to the turbid clayey material, which has been shown to be high in alumina and low in potash. This introduces further complications regarding the potash content of these rocks. The dominance of potash over alumina is a characteristic and most puzzling feature of the rocks of this suite (Wade and Prider, 1940, p. 74); if potash has been removed from the original leucite as indicated by this investigation, then the groundmass must contain considerably more potash than was previously thought.

The replacement of olivine by nontronite is unusual and does not appear to have been previously recorded.

The authors consider that these replacements (both of olivine and leucite) have been effected during a late magmatic stage and are not due to weathering. The facts (1) that the "clayey" alteration of leucite is so uniform throughout the suite, in otherwise perfectly fresh rocks, and (2) that the central parts of the original leucites are most affected while the outer orthoclase rim is unaltered, seem to point to late magmatic effects rather than weathering processes as being the dominant cause of the alteration.

ACKNOWLEDGMENTS

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NOTES AND NEWS

USE OF AMMONIUM HYPOPHOSPHITE IN DETERMINATIVE MINERALOGY

ERNEST E. WAHLSTROM,

University of Colorado, Boulder, Colorado.

The attention of mineralogists and chemists should be directed to the ammonium hypophosphite test for certain metals as recently described by Van Valkenburgh and Crawford (1). The test, which was developed and perfected in the chemical and mineralogical laboratories of the University of Colorado, has been used sufficiently to demonstrate its superiority over many of the well established procedures of determinative mineralogy. The present writer has utilized the test successfully with many simple and complex mineral aggregates. Students quickly master the details of the technique and are enthusiastic in their support of the merits of the test.

Ammonium hypophosphite ($\text{NH}_4\text{H}_2\text{PO}_2$) is cheap and easily procured. The writer uses hypophosphite manufactured by the Mallinkrodt Chemical Works and labelled "for manufacturing use only." There is no great advantage in using an expensive, chemically pure reagent.

The procedure for making a test is as follows: about 0.1 gram of finely powdered mineral is mixed with 2 grams of ammonium hypophosphite and heated over a Bunsen burner flame in a porcelain evaporating dish. Decomposition of the hypophosphite produces various gases which ignite and yield thick white clouds of smoke. Heating is continued until a clear fusion is obtained. The fusion is water soluble.

Cobalt, titanium, and tungsten all produce blue melts when hot, but cobalt causes the fusion to turn pink upon cooling. To test for tungsten, add a shallow layer of water to the cold melt and allow it to stand for a few minutes. If tungsten is present the melt will gradually turn deep violet. The speed of this reaction depends on the rate at which the water penetrates the fused mass and on the concentration of tungsten. A shallow water layer above a fusion containing titanium assumes a delicate rose color. To confirm the presence of titanium add hydrogen peroxide, which produces a strong orange-red color in the solution.

Vanadium, chromium, and uranium all color the cold fusion green. The vanadium fusion is distinctive in that it is reddish when hot and changes through yellow to green as it cools. A water layer over the vanadium melt becomes pale green on standing and turns pink upon addition of hydrogen peroxide. To prove the presence of uranium, add sufficient ammonium carbonate to a water layer over the melt to make a distinctly basic solu-

tion. Then add hydrogen peroxide, when, if uranium is present, the solution will turn yellowish orange. If the green color of the melt is caused by chromium, hydrogen peroxide will not cause any color change.

Molybdenum in all minerals, except molybdenite, gives a reddish-brown fusion. With molybdenite the melt is covered with concentrated nitric acid, the acid is boiled off, and the mixture is fused again. With such treatment the fusion assumes a blue or blue-green color. Addition of water causes the melt to turn yellow.

Manganese produces a colorless melt. When concentrated nitric acid is added and the mixture is boiled to remove the excess acid, the melt assumes the familiar permanganate purple.

Tellurium in minerals is freed to produce small metallic globules which float in the melt. Strong heating for two or three minutes causes wine-colored aureoles to form around the globules. Water changes the wine color to black.

Columbium ordinarily is associated with tantalum. Accordingly, a positive test for columbium indicates the presence of tantalum. Fusions of columbium minerals in ammonium hypophosphite are colorless. The mineral powder rarely completely disintegrates. Concentrated hydrochloric acid is added to the fusion, the mixture brought to a boil and a small piece of mossy tin added. If columbium is present, a brilliant blue color results.

Conceivably, mineral mixtures may occur in nature that will not yield satisfactory tests, but in ordinary laboratory procedure involving the examination of pure minerals or simple aggregates, no difficulty will be encountered. The tests are sufficiently sensitive for most purposes. Depth of color in the melt and rate of reaction upon addition of water or acid permit rough quantitative estimates of metallic content.

The writer is indebted to Dr. Van Valkenburgh and Mr. Crawford for permission to make the results of their work available to mineralogists.

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- (1) VAN VALKENBURGH, H. B. AND CRAWFORD, T. C., Detection of certain metals in minerals and ores: *Industrial and Engineering Chemistry*, **13**, 459 (1941).

STRUVITE IN CANNED LOBSTER

VINCENT L. AYRES,

Michigan College of Mining & Technology, Houghton, Michigan.

For an authentic mineral species struvite, $\text{NH}_4\text{MgPO}_4 \cdot 6\text{H}_2\text{O}$, has numerous strange occurrences. As given in Dana's *Manual* it has been "found in guano from . . . the coast of Africa; also under an old church in Hamburg, where quantities of cattle dung existed in the soil above a bed of peat which contained the crystals; (and) in the bat guano of the Skipton caves. . . ." A further interesting occurrence for the mineral is indicated by a recent discovery of a crystal group inside a lobster's claw.

The struvite was brought to the writer for identification at a time when he was attempting to find an orthorhombic crystal suitable for measurement on the two-circle goniometer. None of the faces was smooth enough for first-class images; nevertheless several of the crystals were mounted by a student, Paul W. Zimmer, and were found to give results sufficiently accurate for identification of the species. The average readings differed 4 to 20 minutes from the values given in Dana for the angles.

The crystal habit was found to be elongated parallel to the a -axis with the brachydomes q $\{011\}$ and h $\{021\}$ predominating, and terminated at the unattached end by the prism p $\{120\}$. The pinacoids b $\{010\}$ and c $\{001\}$ in the elongated zone gave in general scattered images, and a doubtful form corresponding to $\{013\}$ was recorded. The only trace of hemimorphism was the presence of a single macrodome face of s $\{101\}$, instead of both in the termination of two of the crystals.

The orientation of the mineral is worthy of comment. Our first attempt was to choose what later turned out to be q as the unit prism and p as a brachydome, giving the $a:b:c$ ratio of 0.912:1:1.133. Neither the c nor the a values could be found in Wherry's Tables.¹ By interchanging the a and b axes and dividing by 2 we arrived at a Goldschmidt value of 0.548 for a ; and by recalculating c , and again dividing by 2, we obtained 0.620 for c . Dana has a still different orientation, more acceptable because he places the hemimorphism along the c axis. In terms of Dana's $a:b:c$, Goldschmidt's and ours are respectively;

$$b/2:c:a \text{ and } c:b:2a.$$

After the mineral was determined crystallographically, confirmatory tests were made microscopically and chemically. The refractive indices, α , β , and γ , agreed with Larsen's values² and the two good cleavages gave flash field and acute bisectrix interference figures. The presence of phos-

¹ *Am. Mineral.*, 5, 164 (1920).

² *U.S.G.S., Bulletin* 848, The Microscopic Determination of the Nonopaque Minerals.

phorus was confirmed with the ammonium molybdate test, magnesium with titan yellow, and ammonia with Nestler's reagent.

That this occurrence of struvite in canned lobster has a close parallel is shown in *Chemical Abstracts*. L. H. James³ reports that some supposed pieces of glass in canned salmon proved to be crystals of struvite; and that such crystals have been found in canned shrimp. C. H. Manley⁴ suggests that local decomposition, not necessarily of a harmful character, is the origin of the crystals; and comments that struvite has been found in ambergris. Struvite has also been found in a human lung.⁵

³ *Analyst*, **58**, 222 (1933).

⁴ *Analyst*, **58**, 337 (1933).

⁵ Porter, Mary W., *Am. Mineral.*, **9**, 93-94 (1924).

EVIDENCE OF SULPHIDE-SILICATE IMMISCIBILITY AT
GAP NICKEL MINE, PENNSYLVANIALOUIS MOYD,
Bancroft, Ontario, Canada.

There has been much controversy over the importance of sulphide-silicate liquid immiscibility in the genesis of the nickel deposits that are associated with basic rocks. Except that the position of the ores in the igneous bodies supports the idea of gravitative settling of fluid sulphides, little field evidence in favor of the theory has been noted. Some observers require as proof the occurrence of globules of one component suspended in a matrix of the other. Grout¹ mentions that during slow crystallization, the globules might lose their rounded form, and believes that the sulphides at Sudbury have passed through this stage. In material from the Gap Nickel Mine in Pennsylvania, the writer believes that evidence of sulphide-silicate unmixing is offered by rounded masses of amphibole occurring in the sulphide matrix.

The Gap Nickel Mine is located on Mine Ridge, in Lancaster County, 3 miles southwest of the town of Gap, on the main line of the Pennsylvania Railroad and the Lincoln Highway, about 50 miles west of Philadelphia. Copper was mined here intermittently as early as 1718, with little success. In 1852, a miner who came from Cornwall, England, noticed that the pyrrhotite was being thrown on the dumps as worthless. He suggested that the company have this mineral analyzed and Dr. Fredrick A. Genth, noted Philadelphia chemist and mineralogist, found nickel in it. The mine was then worked for nickel, at first unsuccessfully. In 1862, Mr. Joseph Wharton took over the mine, remodeled the works, and established a nickel refining plant in Camden, New Jersey. He prospered in this venture, and in 1876 the mine produced one-sixth of the annual world's output of nickel. However, the next year the higher quality ores from New Caledonia entered the market. The commencement of production at Sudbury a few years later led to a complete shut-down of the Pennsylvania operations in 1893. At present the workings are inaccessible and any study of the deposit must be made from old reports and from material on the dumps, which are extensive. The sulphides exposed to the weather are becoming quite oxidized and in a few years will be completely broken down.

The ores occur in a lenticular body of amphibolite, about 2000 feet long and 800 feet across at its widest part. This mass intrudes a schistose facies of the pre-Cambrian Baltimore gneiss, the long axis of the lens paralleling the strike of the gneiss, roughly east-west. Kemp² noted that

¹ Grout, F. F., *Petrography and Petrology*, New York (1932), p. 223.

the amphibolite lens showed a marked lamination or gneissoid structure at the west end, but was more massive toward the east. The laminations run parallel to the major axis of the body and he ascribed this structure to dynamic metamorphism and shearing. The amphibolite is composed almost exclusively of green hornblende. Kemp considered most of this to be uralitic in origin and found traces of pyroxene and olivine, which he considered to have been the original minerals of the rock. Phemister³ believes that only a small portion of the hornblende is uralitic and that the major portion is a direct crystallization product of the magma, a view shared by the writer. Some plagioclase and sphene are present in the

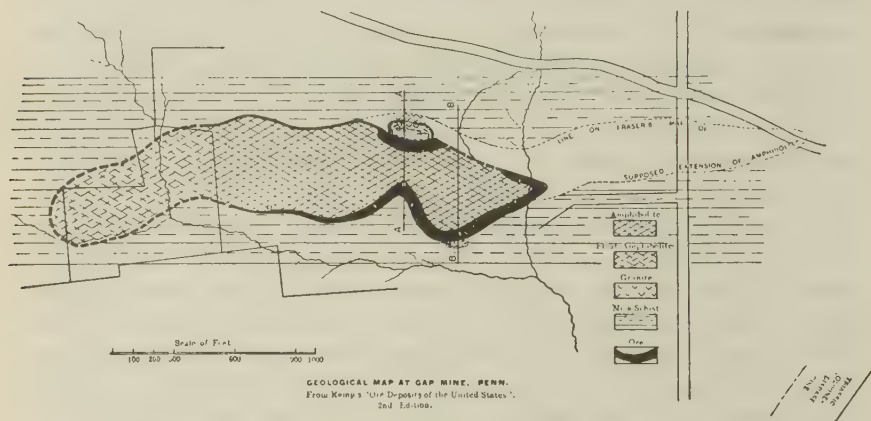


FIG. 1. Geological Map at Gap Mine, Pennsylvania, From Kemp's *Ore Deposits of the United States*, 2nd Edition.

basic rock and biotite replaces some of the hornblende. The sulphides are found along the margins of the body, favoring the east end and thinning toward the west. In some places the ore was as much as thirty feet thick. The sulphides fade out gradually into the amphibolite as the contact is left, although some workable masses of ore were found well within the lens. Little or no ore has penetrated the schistose country rock. Cutting the body are a few small pegmatites, also quartz veins bearing siderite, sulphides and crystallized vivianite. Joint planes are covered with crusts of millerite which added considerably to the value of the deposit. The ore itself is composed of pyrite, chalcopyrite, and pyrrhotite with exsolved pentlandite.

² Kemp, J. F., Nickel mine at Lancaster Gap, Pennsylvania, and the pyrrhotite deposits of Anthony's Nose: *A.I.M.E., Trans.*, **24**, 620-633 (1895).

³ Phemister, J. C., A note on the Lancaster Gap mine: *Jour. Geol.*, **32**, 500-502 (1924).

Campbell and Knight⁴ in their classic study of polished sections of nickel ores, describe the Gap ore as being composed of medium sized grains of pyrrhotite, which were apparently badly strained. Around the pyrrhotite are veins and masses of pentlandite with characteristic cleavage. Chalcopyrite is closely associated with the pentlandite and is probably later, as it is molded against and includes grains of it. Magnetite occurs as octahedra and there are crystals of hornblende with ragged terminations. Campbell and Knight studied only one section from the deposit, which did not contain pyrite. From blocks on the dumps, especially those in which the other sulphides are considerably weathered, well-formed octahedral crystals of pyrite up to $\frac{3}{4}$ inch in diameter can be obtained. Undoubtedly pyrite was the first of the sulphides to crystallize. Throughout the ore are masses of hornblende, many of them rounded and varying in size, but most of them are about an inch in diameter. These stand out as knobs where the ore has been exposed to the weather. Polished specimens show that beside these nodules, there are detached fragments of hornblende crystals in the sulphides, and sulphide veinlets cut across and seem to be replacing the masses of amphibole.

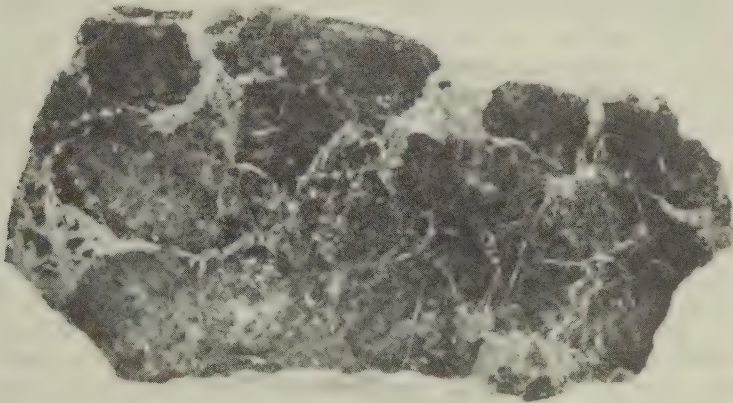


FIG. 2. Polished section from Gap Mine showing hornblende nodules in sulphide matrix. Fractures in the nodules are filled with sulphides.

As to the genesis of the ore-body, Kemp considered the sulphides to have crystallized contemporaneously from the igneous mass. Campbell and Knight believed that the sulphides, carried by solutions, penetrated

⁴ Campbell, W. and Knight, C. W., On the microstructure of nickeliferous pyrrhotites: *Econ. Geol.*, **2**, 350-366 (1907).

and replaced the fractured basic rock. Phemister notes the evidence in favor of each hypothesis. He finds that an igneous view is favored by the fact that the contact of the ore and amphibolite is gradational, while the contact of ore and schist is sharp. Also, that the amphibolite shows the presence of sulphides throughout its extent. He considers as insurmountable evidence against magmatic origin of the sulphides that they are distinctly later than the silicates and replace them, this replacement having proceeded in many cases along small fractures. He gives as the sequence of formation of the ore, the intrusion and crystallization of the basic body which was followed by forces causing fracture and deformation, then, the ascent of ore-bearing solutions along the contacts, reacting with and replacing the silicates. As a possible source of these solutions, he refers to the pegmatites and quartz veins throughout the area. However, these are notably barren of ore minerals and nowhere have large concentrations of sulphides been introduced into the seemingly favorable schistose country rock adjacent to the deposit.

If what has been regarded as insurmountable evidence of replacement of the amphibolite by sulphides can be explained in another manner, then nothing would stand in the way of considering the Gap ore-body as an example of the syngenetic emplacement of basic rock and nickel ore. Should the nodules of hornblende, surrounded and penetrated by sulphides, be considered as the crystallized remnants of once-liquid silicate globules suspended in a bath of molten sulphide, then the following succession of events in the genesis of the deposit becomes apparent.

First, the intrusion at a high temperature of a small basic laccolith into the Baltimore gneiss. As the magma cooled, sulphide and silicate became less soluble in each other and began to separate, the heavier sulphide being carried toward the base of the body by gravity. With continued cooling, the magma became more viscous and the settling of the components was hindered, causing the sulphides separating from solution in the upper levels to be trapped in the silicate, and the silicate material coming out of solution in the lower zones to form globules in the fluid sulphide matrix. Then the silicate crystallized, but with the interstitial and underlying sulphide still fluid. At this stage the body was subjected to dynamic action which caused it to buckle into its present lens form, and sheared the amphibolite into gneissic form in the portions where interstitial sulphide was sparse, but caused only fracturing where the rock was protected by the molten sulphide. The fluid sulphide penetrated the small fractures, isolating fragments, and formed a structure resembling somewhat that resulting from metasomatic processes. The first sulphide to crystallize was pyrite, in euhedral form, then pyrrhotite. Dynamic action was continued to this point, causing the strain noted

earlier, and making channels for the last of the sulphides, chalcopyrite, to penetrate. At this stage, solid pentlandite was thrown out of the cooling pyrrhotite, in accordance with the findings of Newhouse,⁵ and chalcopyrite crystallized around them. Some time after the complete crystallization of the body, it was penetrated by pegmatites and quartz veins, which might possibly have re-activated some of the sulphides to form the quartz-siderite-sulphide-vivianite veins, and which could have caused a minor amount of replacement of the silicates by sulphides. The millerite coatings on the joint planes were probably deposited by downward penetrating surface waters, as a considerable gossan was found.

⁵ Newhouse, W. H., Equilibrium diagram of pyrrhotite and pentlandite and their relations in natural occurrence: *Econ. Geol.*, **22**, 296 (1927).

Attention is called to the new Special Paper #36, "Handbook of Physical Constants" of geological materials published January 31, 1942, by The Geological Society of America. The volume contains 21 sections prepared by 19 specialists cooperating through the Divisions of Chemistry, Physics and Geology of the National Research Council. Copies may be consulted in geological libraries and are available to the public at a price of \$1.40 on application to The Geological Society of America, 419 West 117 Street, New York, N. Y.

Professor C. K. Leith of the University of Wisconsin, at present Adviser to the Materials Division of the United States War Production Board, gave a series of ten lectures under the auspices of the Division of Geology and Geography of Columbia University, entitled "Minerals in Peace and War."

Sir William Bragg, Fullerian professor of chemistry of the Royal Institution, London; director of the Davy-Faraday Research Laboratory; and president of the Royal Society from 1935-1940, died on March 13 in his eightieth year. In 1915 he shared the Nobel prize with his son, William Lawrence Bragg, for their work on x-rays and crystal structure.

BOOK REVIEWS

OPTICAL MINERALOGY by AUSTIN F. ROGERS AND PAUL F. KERR. xvi+389 pages, 369 figures. McGraw-Hill Book Company, New York, 1942. Price \$3.75.

This is a second edition of the well known Thin-Section Mineralogy by the same authors. The change in title was made because Thin-Section Mineralogy found application in other forms of microscopical identification of minerals with the microscope. In the preface to the second edition the authors state that many explanations of optical properties have been rewritten, new diagrams have been added and descriptions of a number of mineral groups have been rewritten.

It is apparent to one familiar with Thin-Section Mineralogy that the authors have made a thorough revision, although the general form of the book is the same. Over 100 new figures have been added, including diagrams explaining optical phenomena, orientation diagrams, and excellent photomicrographs of minerals. A new chapter on the observation of mineral fragments includes directions for the use of the immersion method and data on the preparation, and care of immersion media. To the identification tables have been added charts showing the range of refractive indices of isotropic, uniaxial, and biaxial minerals and the range of axial angles of biaxial minerals.

In Part II, Descriptions of Individual Minerals and Mineraloids, some groups of minerals have been revised and expanded to list separately species grouped in the previous edition. An example is *pigeonite* now described separately but formerly included with *augite*. The pyroxenes, amphiboles, olivines and chlorites have thus been expanded. In addition a few individual minerals have been added. Descriptions of monoclinic and triclinic minerals include the axial angles between the crystal axes. The list of names of minerals include several new ones, such as *lamprobolite* suggested by the senior author for basaltic hornblende and *serpophite* used by Lodochnikov for structureless serpentine with weak birefringence.

Little fault can be found with this book. It is planned as a text for a first course in optical mineralogy and as such admirably meets its purpose. The reviewer would prefer that the optics of uniaxial crystals be separated from those of biaxial crystals and that isomorphous relations of some groups of minerals be more closely related to specific optical properties. He also feels that the description of the Berek compensator is somewhat superfluous because this apparatus is not available to most beginning classes in optical mineralogy. Students occasionally are puzzled by orientation diagrams arranged with the vertical axis placed in a horizontal position in the book, an arrangement found in this edition as well as in the first edition. The publisher has done his usual good job of book making and the cost of the book is not unduly high.

JOHN T. LONSDALE

DIAMOND AND GEM STONE INDUSTRIAL PRODUCTION by PAUL GRODZINSKI. Octavo, 256 pages, with 183 figures and 32 tables. N. A. G. Press, Ltd., London, 1942.

This is the first book in English to discuss the cutting of the diamond for both gem stone and industrial purposes. It is well known that the great progress which has been made in recent years in precision machining has been largely due to the use of diamond-set tools, and that the more rapid drawing of metallic wires and filaments which accurately meet prescribed specifications has been made possible through the increased use of wire drawing diamond dies. The use of diamonds for these purposes involves careful preparation and accurate shaping which are not necessary with carbonado and boart as used in diamond drill bits.

Up to the present time the only volume available dealing with the use of the diamond

in industry has been Grodzinski's *Diamant-Werkzeuge*, which was published in Berlin in 1936. As is easily understandable, this volume has had little circulation in this country. However, Grodzinski's new text, *Diamond and Gem Stone Industrial Production*, which has been prepared to meet the increasing demand for authoritative information in this important field, undoubtedly will be used extensively. This should be the case in Great Britain and the United States where the enormous defense programs call for greatly increased production of diamond-set tools and wire drawing diamond dies, especially since the principal source of the latter was formerly France and the Low Countries.

The book contains fourteen chapters, the first eight dealing with general methods while the last six discuss special manufacturing methods. There are also three appendixes containing very helpful tables, and a short selected bibliography. While the main emphasis is on the diamond, the cutting and polishing of other gem stones receive some attention.

The treatment is general in character and does not assume an extensive background as far as the crystallography and mineralogy of the diamond are concerned, or considerable experience in the cutting processes. In some instances the descriptions of the construction and the functioning of the machines which are illustrated are too concise and are not clear. It is to be regretted that more care was not exercised in orienting properly the various crystal drawings. This applies especially to Figs. 6, 11, 86, 87, and 88A.

The N. A. G. Press, Ltd., London, is to be congratulated in bringing out this useful volume during this very critical war period.

EDWARD H. KRAUS

PROCEEDINGS OF SOCIETIES

PHILADELPHIA MINERALOGICAL SOCIETY

The Academy of Natural Sciences of Philadelphia, November 6, 1941

Dr. W. Hersey Thomas presided, with 83 members and visitors present. Mr. Charles R. Toothaker, Curator of the Commercial Museum, addressed the society on "Curious Uses of Minerals."

December 4, 1941

Dr. W. Hersey Thomas presided with 73 members and visitors present.

Dr. E. G. Zies of the Geophysical Laboratory addressed the society on "Volcanos and Fumaroles."

January 8, 1942

Dr. W. Hersey Thomas presided with 43 members and visitors present. President Thomas introduced the speaker of the evening, Dr. Joseph Gillson, who spoke on "The Relation of Ilmenite Sands of Brazil to the Physiography of Brazil" Dr. Gillson gave a review of his experiences and geologic discoveries on a recent trip to the eastern coast of Brazil. His account covered the region along the coast from Rio de Janeiro northward about 700 miles.

The history of the land surface development and the relation of the land to the sea has been the critical factor in the development of the ilmenite deposits. At the end of the Cretaceous period there was a deep soil zone on the land. With the uplift, the first erosion carried this soil down to the sea so that the bottom of the Tertiary sedimentary deposits is formed of the material from this soil zone. It is in these bottom layers that the ilmenite was first deposited. Reuplift and erosion of the Tertiary sands caused a reworking of the sands by the waves and by off-shore currents. Being heavy the ilmenite was deposited on the beaches where waves were attacking the Tertiary cliffs, or it was concentrated in off-shore bars that were being built up across the mouths of the estuaries. The latest uplift has

raised these old beaches and bars above the sea. The best deposits are found in these old estuaries.

The "ilmenite" of Brazil is really arizonite and not ilmenite, as is also the well known "ilmenite" of India. The formula for arizonite is $\text{Fe}_2\text{O}_3 \cdot 3\text{TiO}_2$ and that of ilmenite $\text{FeO} \cdot \text{TiO}_2$.

The lecture was illustrated by the use of excellent kodachrome slides.

Mr. Toothaker made some interesting remarks concerning the precious metals and gems that are located on this plateau in Brazil. These minerals are also found in the river gravels that traverse the Tertiary deposits and probably have been eroded from the pegmatite dikes that traverse the gneissic mountain formations.

FORREST L. LENKER, *Secretary*

NEW MINERAL NAMES

Brodrickite

H. C. DAKE: Brodrickite—a new mineral. *The Mineralogist* 9, No. 12, 443–444 (1941). With microscopic study by E. E. Fairbanks, U. S. Bureau of Mines, College Park, Md.

NAME: For John H. Brodrick, who collected the mineral.

CHEMICAL PROPERTIES: "Quantitative study by means of the spectroscope proved the new mineral to be essentially a magnesium aluminum silicate with K_2O 1.0–2.0, Fe_2O_3 1.5, Rb_2O 0.1–0.2, Li_2O 0.1%, CaO trace, Na, Cs, Cr, none."

PHYSICAL AND OPTICAL PROPERTIES: "Cleavage micaceous excellent, with cleavage flakes inelastic and greenish-yellow in color. Optically biaxial negative, with an optic axial angle of approximately $12-15^\circ$. The refractive indices of gamma and beta are slightly greater than 1.560. Both are less than 1.565 and are nonpleochroic."

X-RAY DATA: The powder diffraction pattern spacings are given. "The pattern differs from that of the chlorites, phlogopite or vermiculite. Enough similarity with phlogopite does exist to suggest a somewhat similar although less well defined or altered structure."

OCCURRENCE: Found in the old limestone quarry, Boston, Mass.

DISCUSSION: The micas and their alteration products are already overburdened with names based on insufficient data. A mineral worthy of a new name is certainly worth a chemical analysis. Brodrickite may possibly be closely related to pholidolite.

MICHAEL FLEISCHER

TEACHING FELLOWSHIP IN MINERALOGY

A teaching fellowship in mineralogy has been established at Stanford University. The fellowship is open to graduate students who intend to specialize in mineralogy, and preference will be given to those who have had one or two years of graduate work. The chief duty of the fellow is to assist in laboratory instruction. Not more than eight or nine hours a week will be required. The amount of the fellowship is \$750.

Application for the year 1942–43, supported by testimonial letters, should be made to Professor Austin F. Rogers, Box 87, Stanford University, California.